Transient Fashion:

A Transdisciplinary Framework For Developing Casein-Based Materials Within A Regenerative Textile Economy

Marie Stenton

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By Marie Stenton

This thesis submitted in partial fulfilment of the requirements for the degree of Marie Stenton at the University of the Arts London; in collaboration with the University of Leeds.

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Supervisory Team:

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COVER IMAGE: Lab-produced woven textile sample, blackcurrant dye.

IMAGES: All photographs are by Marie Stenton unless otherwise noted.

WORD COUNT: 82,632

ABSTRACT

As the global population continues to grow and consumer trends favour disposable goods, there is mounting pressure on the world's resources and a concerning surge in waste production. This issue is acutely evident in fashion and textiles, where the phenomenon of 'fast fashion' has driven demand to unprecedented levels. Sustainable practices within the Fashion and Textile Industry (FTI) often focus on implementing a circular economy model to minimise waste by maximising resource utilisation. However, existing solutions tend to address isolated aspects of the supply chain, such as the switch to recycled materials. At the same time, critical elements like chemical processing and textile dyes remain largely unexamined as part of a holistic design and manufacturing process.

The intricate nature of these challenges underscores their interconnectivity. To address these complexities, this thesis advocates for a regenerative approach that explores the potential of food waste streams as a commercially viable and circular source of raw materials for the FTI. This study utilises a transdisciplinary methodology that converges textile design, green chemistry and archive data to investigate the feasibility of creating regenerated casein fibres from dairy industry waste. This investigation is carried out through a multifaceted approach, encompassing both laboratory-based experimentation and studio-based material and garment development. By leveraging the synergies of transdisciplinary practice, this research seeks to disrupt the prevailing paradigm of mass-produced fashion and contribute to a regenerative future for the FTI.

CONTENTS

ACKNOWLEDGEMENTS

Firstly, thank you to my PhD Supervisors and the WP6 team: Professor Veronika Kapsali, Professor Richard Blackburn, Professor Jane Harris, Dr Joseph Houghton, and Hannah Auerbach George. I would especially like to thank Dr Joseph Houghton, who went above and beyond not only to be my supervisor and mentor but also a great friend who helped me navigate the chaos and pressure of undertaking a PhD. Thank you for your patience, for answering my constant stream of chemistry questions and for organising my lab visit so I could test your incredible spinning rig first-hand (and for rearranging when I got COVID and couldn't make it the first time).

This research was only possible with funding from the BFTT. Thank you for choosing me to undertake this project and allowing me the opportunity to be a part of the BFTT research community. I am also thankful to the Bath and Bristol Creative R&D programme for the New Scholars Fellowship. This funding allowed me to travel to America to conduct valuable research, travel to conferences, and purchase various equipment to continue my research at home during lockdown.

To my Director of Studies, Veronika, thank you for challenging me to think outside the box and for your constant guidance and support, academically and emotionally. When I was diagnosed with dyslexia in my first year of study, you helped me navigate the perils of academia with what you referred to as 'my superpower'. Your kind words kept me going through the toughest times.

I would also like to thank Hannah, whose knowledge and expertise in textiles and weaving proved invaluable. You helped push the textile development and allowed us to produce two collections of woven samples, which were integral to the research process. Again, you were not just a colleague but became a great friend. You, Joe, and I really were the dream team. I hope to be of the same support when you start your PhD later this year.

To Professor Kate Goldsworthy, thank you for inspiring me to push the boundaries of what defines sustainability. Your work on Speedcycles made me question our current relationships with fashion and quality and paved the way for Transient, Casein-based Garments (even when my decision to explore fast fashion was criticised). Alenka Tiddar and Kristina Hetherington at Keracol, thank you for taking me under your wings and giving me a crash course on the chemistry of natural dyes.

To all of the incredible women in my life, Liv, Gabby, Becky, Ella, Sarah M, Sarah W, and my sister Rachael, who has brought my beautiful niece and nephew into the world in the duration of this PhD, for your friendship and counsel over the years. Your strength and hope never cease to inspire me.

To my parents, Julia and Dave: Thank you for your endless support and encouragement. Hopefully, I can finally stop being a student and get a real job. Thank you for all the ways you have sustained and motivated me over the years, including the emergency shipments of Henderson's Relish.

Most importantly, I thank my husband, Andy, for your constant care and love. Your endless encouragement and belief in me have kept me going these past four years, and your willingness to upheave your northern roots and embark on our London adventure means the world to me. I could not have done this without you, and I will forever be grateful for everything you have done for me.

FOREWORD

My practice has taken a journey over six years of postgraduate study (2 years of MA study and four years of PhD study). Since graduating with a degree in Textile Design from the University of Leeds in 2013, I have spent my time divided between areas of both fashion and textiles, gaining experience in a variety of fields, from working in fashion manufacturing to freelance design and running my own accessories label. This range of experiences led to my understanding of the day-to-day issues surrounding ethics and sustainability across the industry.

As a designer building my own brand ethos, I knew I wanted to use ethically sourced materials but did not know where or how to find them. As a small, independent business, any 'sustainable' fabrics I found were unavailable due to high costs and minimum orders. This frustration led to my return to education to complete an MA in Fashion Design at Sheffield Hallam University. Here, I worked to establish a methodological approach to creating new, circular materials through an open-source design kit. I worked with bacterial cellulose as a tool to explore the process of developing - or, in this case, growing - my own materials and working in a range of non-traditional environments to help remove myself from the usual constraints of design.

During this time, I continued to learn about the negative impacts of the industry and the complex entanglement of issues such as waste, water pollution, deforestation and our reliance on cheap materials derived from fossil fuels. This prompted a shift in mindset away from designing or creating unnecessary products and towards developing systems for change in the industry.

The Business Of Fashion, Textiles And Technology

This PhD is in partnership with The Business of Fashion, Textiles and Technology (BFTT) Creative R&D programme. This industry-led project focuses on delivering innovation within the fashion and textile supply and creative production chain whilst positioning the industry as agents of new technology and materials development. Within this programme, I am employed under work package 6: Rethinking Material Resources. The following quote outlines the scope of WP6 and the remit of this research study.

> "*Microfibre pollution from synthetic textiles accounts for over one third of plastics in the open ocean. With growing public and consumer awareness, the environmental incentive for rethinking alternative material resources could not be more stark.*
>
> *Meanwhile, the UK food and drink manufacturing industry produces almost 2 million tonnes of waste per annum – the dairy industry being the largest generator of such waste. Much of this waste is inevitable, for example by-products of cheese production, and could be reimagined as a resource.*
>
> *While alternative material development for fashion and textiles may be considered relativley nascent, pioneering chemists in the 19th and 20th Century developed to semi-commercial scale a range of largely-forgotten Regenerated Protein Fibres (RPFs) – including those derived from milk, egg, and soy.*
>
> *Early research focusing on fungi, nettle, hemp and seaweed was also relatively advanced, and emergent technologies have received renewed interest in recent decades. The final technical barriers to widespread exploitation, which halted RPF and non-protein-based fibre innovation in the early 20th Century, can now be overcome."*

(BFTT, n.d.)

The Team

The work package 6 team includes co-investigators Professor Veronika Kapsali (London College of Fashion) and Professor Richard Blackburn (Keracol), post-doctoral research fellows Dr Joseph Houghton (University of Leeds Institute of Textile and Colour) and Hannah Auerbach George (Victoria & Albert Museum) and technical director Dr Meryem Benohoud (Keracol).

Figure 1 illustrates the management structure including programme director, Professor Jane Harris, principal investigator, Professor Goldsworthy and senior researcher, Joanna Norman.

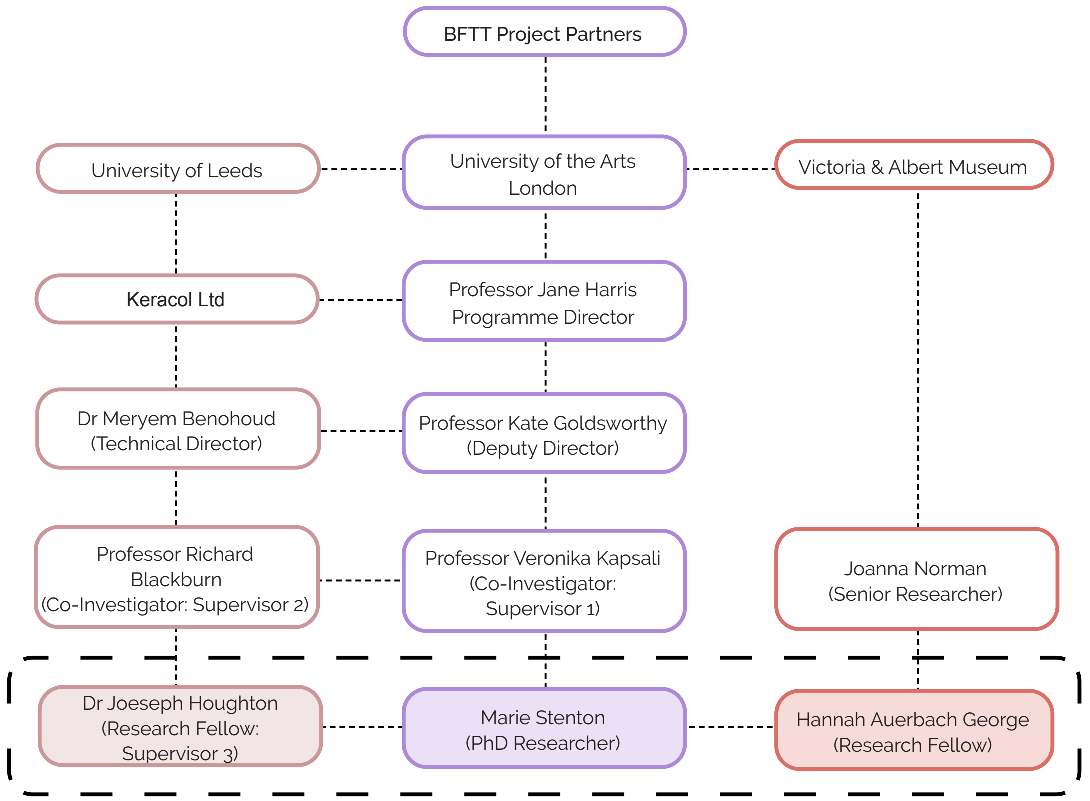

Figure 1: BFTT work package 6 management structure

My Role Within The Project

My research focused on the role of casein as a raw material for a regenerative fashion economy alongside the development of a transdisciplinary design methodology. My role within the project team was to provide a practice-based textile and fashion design perspective. In terms of the specific challenge, this thesis takes a wider approach to assessing the sustainability of casein-based materials, not only from a physical perspective but also from a social and cultural context – for example, exploring consumer habits such as how we interact with and dispose of our clothing and the impact that this has on the environment. Based on this approach, my response to the challenge was to create an original framework using regenerative design practices to create disposable, casein-based products that are intentionally short-lived and fully compostable.

Impact Of COVID-19

The nature and direction of this research project shifted several times throughout its four-year duration. Of course, some of this is due to the fluid nature of the PhD and the research process. However, the week of the 16th of March 2020 (six months into the PhD), the UK went into national lockdown due to the Covid-19 pandemic. During this time, the sense of emergency for a more sustainable way of life could not have been greater.

As universities and research facilities temporarily closed their doors, the structure of this PhD shifted dramatically whilst responding to the challenge of working from home. Several changes in direction are highlighted throughout the thesis, along with the thought process of why and how they were made and what was hoped to have been achieved at the time. The methodological framework considered the uncertainty of the years to come and allowed for a flexible learning and collaborative approach. Any final outcomes were tailored to what was physically possible to produce with limited access to resources and facilities. Despite the limitations, every opportunity was taken to fully explore a range of materials, processes, and techniques by taking an experimental, DIY approach to material development. Conducting this research during such turbulent times pushed the project further into unforeseen directions, highlighting the necessity of creating localised, regenerative systems and challenging mindsets.

Glossary Of Terms

Considering the transdisciplinary nature of this research, various terminology spanning design and scientific disciplines has been employed. As such, a glossary of terms has been curated to enhance the accessibility of this thesis to a wide audience. This glossary considers the diverse backgrounds and areas of expertise of those who may find relevance in this work for their practices or fields of research. Furthermore, it is crucial to clarify the nuanced usage of specific words. For instance, the term 'quality' recurs throughout the thesis but assumes different meanings in varying contexts. To address this, instances where a term is employed in multiple is demonstrated below and distinguished within the text using an asterisk*.

Anthocyanin: A class of water-soluble pigments responsible for the red, purple, and blue colours in many fruits, vegetables, and flowers.

Anthropocene: A proposed geological epoch characterised by the lasting impact of human activities on the Earth's ecosystems and geological processes, including climate change, biodiversity loss, and alterations to the planet's geological strata.

Casein: A protein derived from milk, commonly used in various industries, including food, textiles, and cosmetics, due to its adhesive, binding, and nutritional properties.

Cross-linking agent: A chemical compound that connects polymer chains, enhancing the strength, durability, and stability of materials.

Disposable: Products or items designed to be used once and then discarded, typically after a single use or a short period of use.

Dope: A viscose liquid that has been intentionally mixed with certain substances, known as "doping agents," to alter its chemical or physical properties.

Dope dying: A textile dyeing process in which the colourants, typically pigments or dyes, are incorporated into the polymer solution or "dope" before it is spun into fibres.

Electrospinning: A nanofiber fabrication technique in which an electrically charged liquid or polymer solution is drawn into fine, continuous fibres by electrostatic forces.

Ersatz: A substitute or imitation product used instead of something genuine or of higher quality, often because the authentic item is unavailable or costly.

Fast Fashion: The rapid production and distribution of inexpensive clothing collections often characterised by quick turnovers of trends to meet consumer demand.

Fibre: A flexible, hair-like strand or filament composed of natural or synthetic materials that can be spun into yarn and used in the production of fabrics, textiles, and other materials.

Fossil fuels: Non-renewable energy sources formed from the organic remains of ancient plants and animals that have undergone geological processes over millions of years, including coal, oil (petroleum), and natural gas.

Galalith: A synthetic plastic material initially developed in the early 20th century, primarily composed of casein and formaldehyde.

Holistic: An approach or perspective that considers the entirety of a system, entity, or situation, recognising the interdependence of its various parts and the need to address them collectively for a comprehensive understanding or solution.

Microfibres: Ultra-thin synthetic fibres, typically less than one denier in diameter, commonly made from materials like polyester, nylon, or acrylic.

Quality: The degree of excellence or superiority of a product, service, or outcome, as measured against established standards, expectations, or criteria.

Quality*: A material or garments fitness for purpose in terms of garment longevity and its potential to contribute valuable nutrients to the earth at end of life.

Regenerative fashion: An approach to clothing design and production focuses on restoring and enhancing environmental and social ecosystems by using practices promoting biodiversity, circularity, and ethical labour standards.

Regenerated protein fibres: A category of synthetic fibres produced by dissolving natural proteins, such as casein from milk or fibroin from silk, and then regenerating them into filaments or fibres through various chemical and mechanical processes.

Slow fashion: An approach to clothing production and consumption that emphasises sustainable and ethical practices, focusing on quality, durability, and timeless designs to reduce environmental impact and promote a more conscious and deliberate consumer choice.

Stakeholders: Individuals, groups, or organisations with an interest or concern in a particular project, business, or initiative who can be influenced by or exert influence over its outcomes, decisions, and success. (Unless specified individually, the term 'stakeholders' reflects the collective term outlined here).

Tannin: A group of naturally occurring polyphenolic compounds found in plants, particularly in fruits, seeds, bark, and leaves, known for their astringent taste and ability to bind with proteins.

Transience: Refers to the temporary or fleeting nature of something, characterised by its impermanence and tendency to change or disappear over time.

Wet spinning: A manufacturing process used in fibre production. A polymer solution is extruded through a spinneret into a liquid coagulation bath, causing the polymer to solidify and form fibres.

Wet spun dyeing: A method of textile dyeing where in which the colourants, typically pigments or dyes, are incorporated during the wet spinning process, before drying and converting into a textile material.

Wicked problems: Complex and multifaceted issues or challenges that resist straightforward solutions due to their interconnectedness and uncertainty. Multiple stakeholders with conflicting perspectives and goals make them difficult to define and address.

List Of Abbreviations

RPF's: Regenerated Protein Fibres
FTI: Fashion and Textile Industry
LCA: Life Cycle Analysis
WWI: World War 1
WWII: World War 2
ESR: Experimental Spinning Rig
RDT: Regenerative Design Thinking
RST: Regenerative Systems Thinking
RDF: Regenerative Design Framework
RDW: Regenerative Design Wheel
TCGs: Transient Casein-Based Garments
TRDR: Transdisciplinary Regenerative Design Research
BCP: Blackcurrant Powder
BCS: Blackcurrant Skins
ROS: Red Onion Skins
AK: Dr Alenka Tidder
JH: Dr Joseph Houghton
HAG: Hannah Auerbach George
KG: Professor Kate Goldsworthy
VK: Professor Veronika Kapsali
RB: Professor Richard Blackburn

Work Package Six Outcomes

The outcomes of this project are listed below and account for research conducted collaboratively across the team. It is noted throughout the thesis who is primarily responsible for each contribution. However, each team member recognises that their work is part of a circular and holistic research process which has influenced and advanced each other's contributions as well as their own. The publications support the thesis discussion and are mainly accounted for in the literature review (chapter 2). Again, each publication has been written collaboratively, featuring ideas and conclusions shared between the team.

Publications:

Stenton, M., Houghton, J.a., Kapsali, V. And Blackburn, R.s., 2021. The Potential For Regenerated Protein Fibres Within A Circular Economy: Lessons From The Past Can Inform Sustainable Innovation In The Textiles Industry. Sustainability (Basel, Switzerland), 13(4), 2328.

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Auerbach George, H., Stenton, M., Kapsali, V., Blackburn, R.s., Houghton, J.a., 2022. Referencing Historical Practices And Emergent Technologies In The Future Development Of Sustainable Textiles: A Case Study Exploring "Ardil", A Uk-Based Regenerated Protein Fibre. Sustainability (Basel, Switzerland), 14(14), 8414.

Auerbach George, H., Tregenza, L., Stenton, M., Kapsali, V., Blackburn, R.s., Houghton, J.a., 2023. Challenging Perceptions Of Fast And Slow In Contemporary Fashion: A Review Of The Paper Dresses Trend In The United Kingdom And The United States During The 1960s. International Journal of Sustainable Fashion & Textiles, 2(1), 29-52.

Blackburn, R. S., Houghton, J. A., Stenton, M., & Tidder, A. (2024). A dye–fibre system from food waste: Dyeing casein fibres with anthocyanins. Coloration Technology, 140(3), 393-402.

Houghton, J. A., Tidder, A., Stenton, M., & Blackburn, R. S. (2024). Coloration in Flow: The Potential of In Situ Coloration of Casein Fibers to Mitigate Environmental Impact of Traditional Dyeing Methods. ACS Sustainable Chemistry & Engineering, 12(6), 2130-2134.

Presentations:

Stenton, M, 2021. Utilisation Of Waste Milk For Regenerative Materials. Conference: Waste-Me-Not. Online, 16th November 2021.

Stenton, M., Houghton, J.A., Auerbach George, H., 2022. Transdisciplinary Research Can Enable The Innovative Design Of Textiles Within A Circular Economy To Produce Regenerated Protein Fibres From Food Waste. Conference: 26th Annual Green Chemistry & Engineering Conference. Reston Va, 06-08 June 2022.

Auerbach George, H., Houghton, J.A., Stenton, M., 2022. Transdisciplinary Research Can Enable The Innovative Design Of Textiles Within A Circular Economy To Produce Regenerated Protein Fibres From Food Waste. Conference: Early Careers Research Symposium. V&A Museum, 03 November 2022.

Auerbach George, H., Tregenza, L., Stenton, M., 2023. Challenging Perceptions Of Fast And Slow Fashion: 1960s Paper Dresses And The Concept Of Disposable Garments. Conference: Sustainable Fashion: Transdisciplinary Approaches To Innovation. Royal Society Of Art, 23 May 2023.

Stenton, M., Auerbach George, H., 2023. Harnessing Historical Technologies In The Development Of A Circular Textile Model: The Future Of Regenerated Protein Fibres. Conference: Textile Institute World Conference. University Of Huddersfield, 06 July 2023.

Physical Outcome of WP6:

The design and development of a novel, modular lab-scale wet spinning rig accessible to SMEs and smaller educational institutions. (Designed and developed by JH at UoL.)

A body of textile samples demonstrating the sustainable processing and colouration of casein-based materials using anthocyanins and tannins extracted from food waste.

A body of digital garment designs demonstrating the mono-material fashion design process capable of matching material properties to garment life expectancy.

1

INTRODUCTION

This thesis advocates for applying regenerative design practices utilising casein-based materials to disrupt the conventional model of mass-produced fashion. It commences by addressing the environmental crisis and its intersection with design and manufacturing. This chapter introduces the concept of 'wicked problems'—complex, interconnected challenges—and assesses them against existing sustainability and circular design solutions, clarifying why current approaches are insufficient.

The section 'Rethinking material resources' emphasises the necessity for a comprehensive approach encompassing technology, design, methodology, and mindset. Such an approach is crucial in creating regenerative materials and products that can safely and harmlessly reintegrate with the environment. Building upon this foundation, the chapter establishes a link between the potential of a future regenerative fashion economy and the precedent set by regenerated protein fibres (RPFs) in history.

Finally, this chapter sets the research context, aims and objectives and underscores the imperative for a transdisciplinary approach within fashion and textile industry practices. In the context of this thesis, 'Transdisciplinary Research' refers to collaborative efforts by researchers from diverse disciplines, sharing their expertise to forge innovative conceptual, theoretical, methodological, and translational breakthroughs. These endeavours transcend discipline-specific approaches, converging to address a shared problem.

1.1 Rethinking Material Resources

1.1.1 Global Situation

"The fashion industry can be conceived as a series of interconnected problems, with an enormous economic and environmental burden, multiple, differing opinions and incomplete or contradictory knowledge." (McQuillan, 2020)

Rittel and Webber (1973) Buchanan (1992) and Irwin, (2012) argue that most of the issues faced by designers today are ill-formulated, confusing, and conflicting, defining such complex issues as "wicked problems". The interrelatedness of wicked problems on a global scale requires a transition design approach (Irwin, 2019), spanning climate change, biodiversity loss, poverty, famine and more. In terms of our current global situation, designers must now, more than ever, become aware of the complexities surrounding the FTI and consider alternative approaches within an ecological, planet-centred worldview.

Along with many others, the IPCC (Allen, Antwi-Agyei et al., 2019) and the World Meteorological Organisation (2021) warn that rising global temperatures will have a catastrophic effect on biodiversity loss and climate change. If temperatures rise by 1.5˚C over the next five years, it is predicted to increase risks to "health, livelihoods, food security, water supply, human security, and economic growth." (Allen, Antwi-Agyei et al., 2019). Even if radical changes are implemented, growing population and resource scarcity intensify the need for essential resources such as food, water, and energy (Steffen et al., 2011). According to the latest IPCC report, a 43% reduction in greenhouse gas emissions (GHG) is required by 2030, and a 69% reduction in GHG emissions is required by 2040 to limit global temperatures from rising above 1.5˚C (IPCC, 2023).

Human-related activities have placed one in five species at risk of extinction, whilst over the past 40 years, 70% of the wildlife population has already been lost (Almond, Grooten et al. 2020). The disproportionate impact which humans currently have on the earth has pushed society into a new epoch known as the Anthropocene: a unit of geologic time in which human activity has become the main driver of environmental change (Steffen et al., 2011).

Two core challenges of this time are decreasing our dependency on petroleum resources (as demand continues to increase) and increased competition for land (Steffen et al., 2011). Wicked problems like these are intricately linked to our current social, economic, and manufacturing systems and cannot be solved in isolation. Regarding the fashion industry, Fletcher and Tham (2019) argue that most environmental issues caused are "a consequence of how the current model is structured. The better the (fashion) sector performs (in terms of growth and profit), the worse the problems will get".

Our dependency on petroleum resources has been growing since the Industrial Revolution, followed by the production of the mass-produced automobile in the early 20th century (Turgeon & Morse, 2022). According to OPEC, roughly 70 million barrels of petroleum are produced worldwide daily (OPEC, 2022) for use in products and services of all kinds, including clothing (nylon, polyester, and acrylic). However, the manufacture, use and disposal of such products cause myriad environmental problems, including the release of microplastics (De Falco, Gullo et al., 2018).

The washing of textiles alone accounts for 35% of primary microplastics entering the ocean (Ellen Macarthur Foundation, 2019). Studies are now also beginning to show the impact of microplastics on the human body and life expectancy. One study detected microplastic in the blood of 80% of people tested (Leslie, van Velzen et al., 2022), whilst another found microplastics in the lungs of 11 out of 13 tissue samples (Jenner, Rotchell et al., 2022). These particles can enter the body in various ways, including breathing them in through our air, consuming food and water, drinking from plastic bottles and wearing plastic-based clothing and face masks (Carrington, 2022). Other studies in this area have explored the connection between respiratory symptoms and disease, including cancer, to regular exposure to synthetic textiles (Prata, 2018) and even cellulosic fibres (Pauly, Stegmeier et al., 1998), further evidencing inhalation as an exposure route for microplastics and microfibres.

Global demand for textile fibres has been increasing heavily since the end of the Second World War, and over the past 50 years, how we produce and consume fashion has changed drastically (Stenton, Kapsali et al., 2021). Alongside a growing population, excessive seasonal collections (Webster, 2016), low prices (Bick, Halsey et al., 2018), discounts and promotional campaigns, the ease of online shopping, and the influence of social media (House of Commons, 2019) have pushed individual consumption to the limit (Ciornea, 2020).

In 2020, 109 million tonnes of fibre were produced globally, almost twice as much as in the year 2000. Polyester accounts for 52% of this, with 59.7 million tonnes of virgin petroleum-based fibres produced yearly (Textile Exchange, 2021). The amount of clothing purchased in the EU has increased by 40% in the last few decades (ŠAJN, 2019), and consumption is expected to increase by 63% by 2030 (Pulse of the Fashion Industry, 2017). Over the past decade, the number of items purchased per consumer has more than doubled (Pulse of the Fashion Industry, 2017); however, clothing is not necessarily used or kept in circulation for longer. It is estimated that the average garment is worn only ten times before disposal (Pulse of the Fashion Industry, 2017) and that over half of fast fashion produced is discarded in under a year, most commonly because it no longer fits (Ellen MacArthur Foundation, 2017; TRAID, 2018).

1.1.2 Limitations Of Current Solutions

"As the nature of fashion is based inherently on the continuous process of change and the pressure to become new or be perceived as new, the fashion industry always strives for novelty, producing new garments in response to fast-moving consumer demand." (Hur & Cassidy, 2019)

In contrast to this statement, sustainability is generally associated with longevity or maintenance (Thorpe, 2007). This reflects the two current popular solutions regarding circular fashion: 'design for longevity' (WRAP, 2014) and keeping materials in circulation through short-term waste management approaches such as recycling (Cobbing & Vicaire, 2017). The concept of sustainable fashion, however, often conflicts with the philosophy of sustainability, and it is argued whether "the philosophy of sustainability can be applied to the fashion industry, as these two concepts are inherently paradoxical" (Hur & Cassidy, 2019).

As implied, a circular economy is a closed-loop cycle where the discarded (recycled, reused, or composted) product becomes something of equal value in a continuous cycle (Colerato, 2019). However, most synthetic fibres currently available are derived from petroleum or repurposing PET bottles from the food and drinks industry (Cobbing & Vicaire, 2017) rather than recycled textile products. (Colerato, 2019; WRAP, 2014)

In the UK, around 350,000 tonnes of clothes go to landfill every year (WRAP, 2015), yet less than 1% of all materials in clothes are recycled into new garments (Ellen MacArthur Foundation, 2017). Due to these numbers, it could be argued that solutions such as in-store textile recycling and thrifting are blind-sighting consumers into thinking that they can responsibly dispose of their clothing. In reality, roughly 12% of clothing is shredded and generally used as fillings in products such as mattresses, whilst the rest (73%) ends up in landfill or is incinerated using carbon-intensive processes (Souchet, 2019).

Aside from post-consumer textile waste, textile production uses roughly 93 billion cubic metres of water annually and emits an estimated 1.2 billion tonnes of greenhouse gas emissions from production per year (Ellen MacArthur Foundation, 2017). The textile industry also accounts for 20% of global industrial wastewater pollution. Some of these chemicals are classified as bio-accumulative and persistent, meaning that once in the environment, they are tough (if not impossible) to eliminate (Ellen MacArthur Foundation, 2017).

Using polyester as an example, Figure 2 demonstrates the stages of a linear take, make, waste model, demonstrating the key areas where value is lost, and waste is generated (Inputs and Outputs). Even by closing the loop and recycling or reusing garments at the end of life, such circular strategies often fail to acknowledge individual areas of the supply chain and subsequently fail to reduce various types of pre-consumer waste (such as chemical and water waste during manufacture). Instead, a holistic approach is required to tackle such complex and interrelated issues throughout the supply chain as a whole (Kern, 2022).

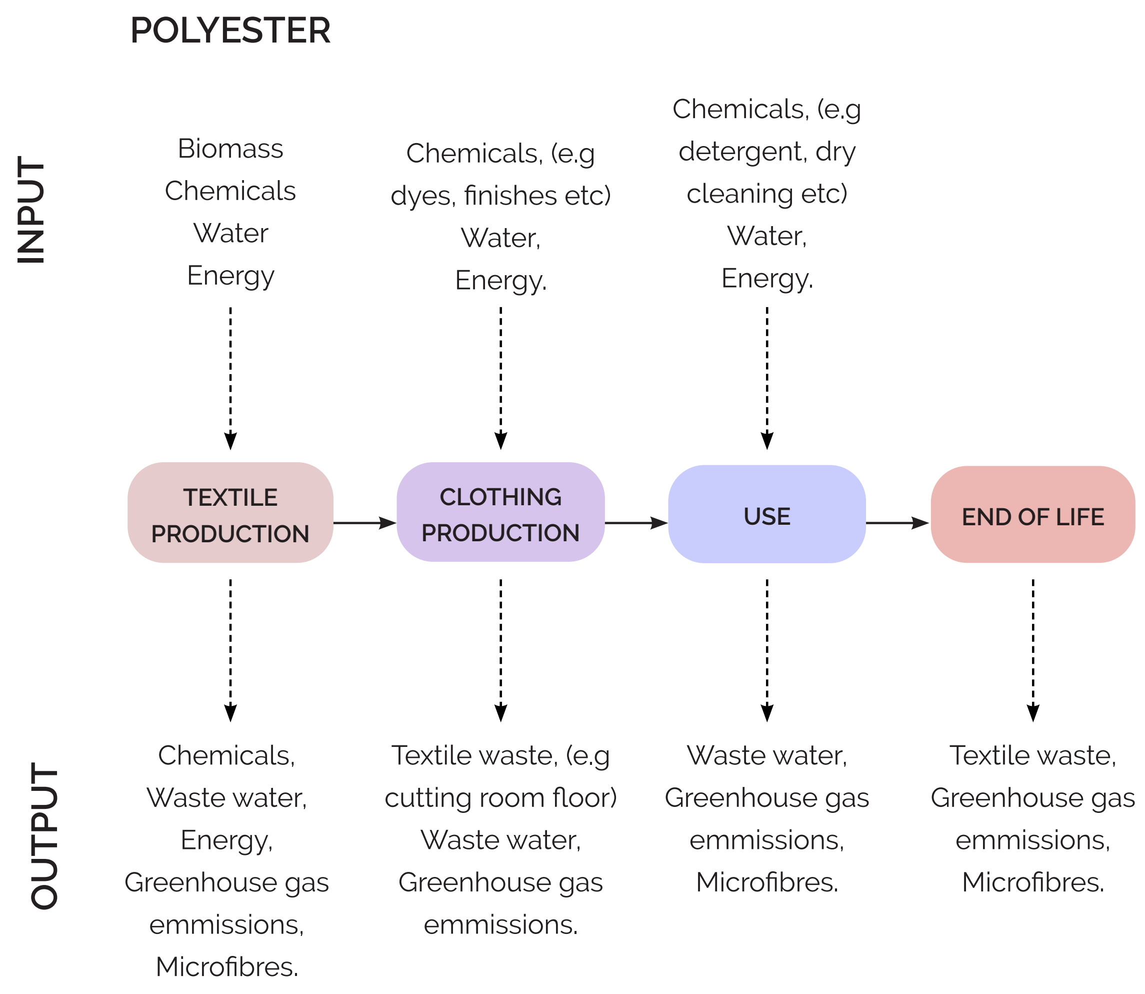


Figure 2: Take, make, waste model highlighting areas of waste.

To reduce waste more holistically, MacArthur (2019) splits material cycles into a technical or a biological circular system to determine the most appropriate way of recapturing value. In the technical cycle, materials are circulated through reuse, repair, remanufacture and recycling. In the biological cycle, nutrients from biodegradable or compostable materials are safely returned to the earth (Elen MacArthur Foundation, 2019). Based on the concept of Braungart and McDonough's Cradle-to-Cradle (Braungart, McDonough et al., 2007), both cycles promote the continuous flow of resources, providing multiple opportunities for reducing waste across the supply chain.

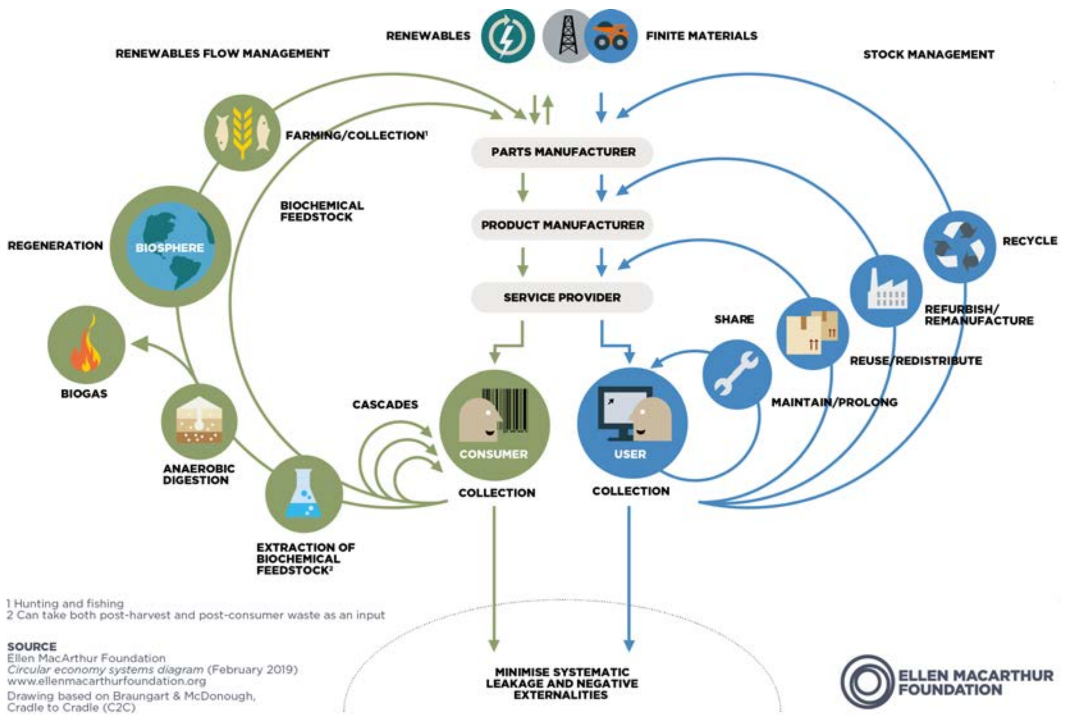


Figure 3: The circular economy system diagram, known as the butterfly diagram, illustrates the continuous flow of materials in a circular economy (MacArthur, 2019).

Although the concept of a circular economy has been criticised in recent years (Abdelmeguid, Afy-Shararah et al., 2022; Nguyen, 2022), this is mainly due to the adoption of a more narrow-minded definition which is commonly reduced to the technical cycle, focusing on aspects such as recycle and reuse (Chan, 2021b). However, the circular economy is vital to reducing resource depletion and should be viewed not as one specific cycle but as multiple cycles working harmoniously.

Recently, a variety of innovative new concepts such as zero waste pattern cutting (Gwilt & Rissanen, 2011; McQuillan, 2020; Rissanen & McQuillan, 2016), design for disassembly (Forst, 2020; Van Balgooi, 2015), upcycling (Goldsworthy & Earley, 2017) and Design for Cyclability (Goldsworthy, 2014) have been adopted by designers aiming to reduce their environmental footprint. These solutions are generally material in nature and, as discussed by Dempsey (2015), while important, 'only touch the surface of a much deeper set of solutions' whilst failing to address the root of the problem.

At the time of writing (2023), an influx of reports challenging our dependency on materials derived from fossil fuels has also come to light. It has become evident that, despite increasing urgency, we (as a society) are still heavily reliant on plastics. An article in the New York Times (Tabuchi, 2022) has outlined how fashion corporations have 'recast plastic' as a favourable material for the planet as recommended by environmental certifications and measuring systems such as the Higg Index (The Sustainable Apparel Coalition, n.d). Most recently, the Higg Index, which has been called out for favouring fossil fuel-derived materials over natural fibres, is under great scrutiny from critics who claim their data is biased, out-of-date, and unrepresentative (Tabuchi, 2022). The Higg Index has also recently been banned in Norway (Deeley, 2022).

The Changing Markets Foundation claims that textile certification schemes are 'acting as sustainability decoys for brands, enabling greenwashing on a massive scale' (Kern, 2022). Their most recent report holds Cradle 2 Cradle (c2c, n.d) and other certifications accountable for allowing members to 'cherry pick' which issues to tackle within their supply chain instead of encouraging a 'holistic set of criteria' (Kern, 2022). As discussed by Goldsworthy (2017), focusing on a limited part of the system can instead create unintended consequences further down the line, a concept known as 'burden shifting'.

Referring to Figure 4, burden-shifting in this way can once again distract from the various and intertwined problems across the supply chain. For example, focusing only on the textile production stage and replacing polyester with recycled polyester creates unintended consequences down the line in failing to address issues surrounding the release of microfibres at numerous stages of the supply chain, the potential mixing of biological and synthetic fibres (creating issues in terms of fibre separation and textile recycling at end of life) and landfill waste.

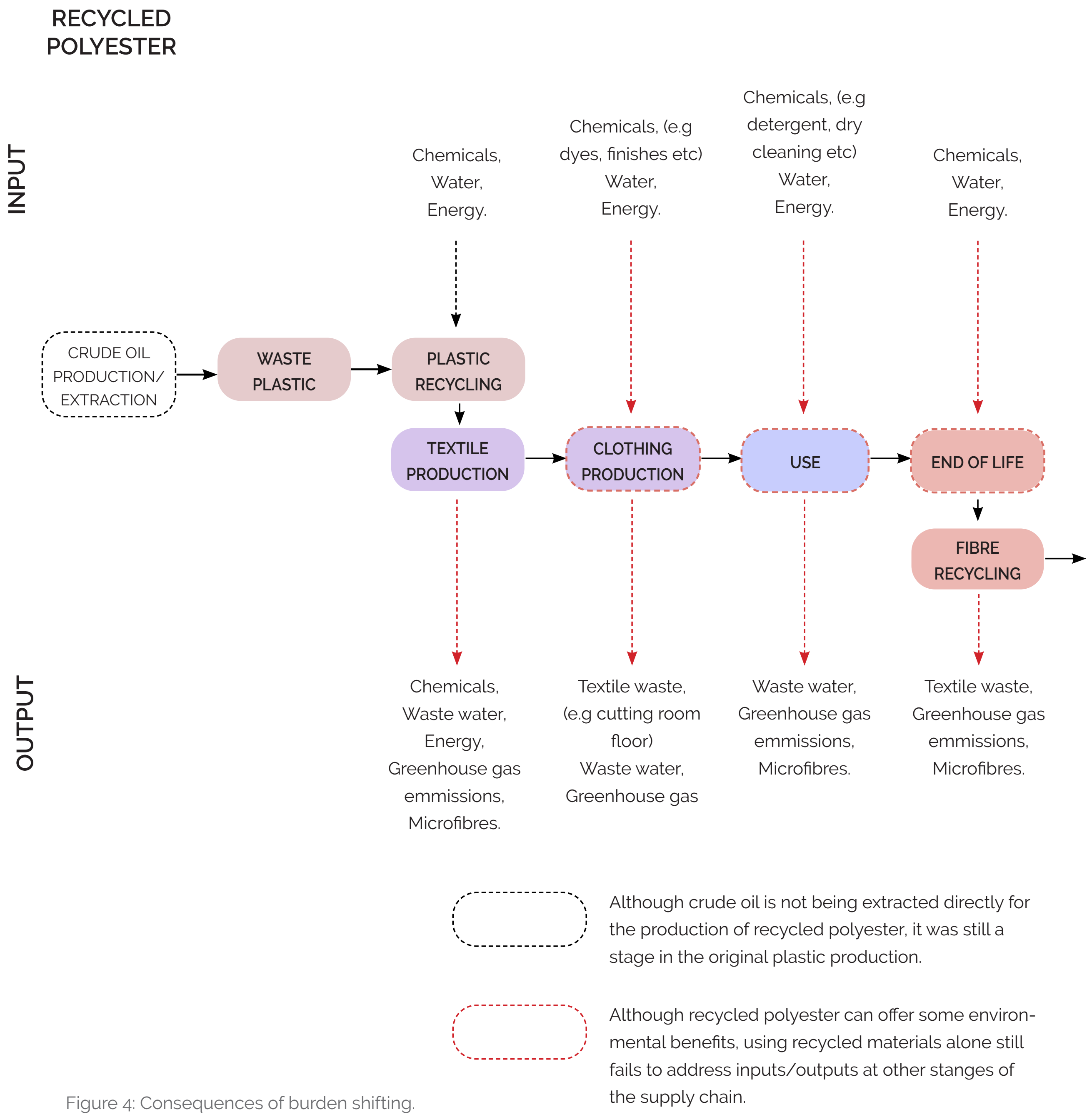


Figure 4: Consequences of burden shifting.

To remove our dependence on fossil fuel materials, McQuillian (2020) suggests a 'transition to natural fibre-based regenerative micro-systems, claiming that radically local textile and fashion production systems could end overproduction and halve consumption. Transitioning to such a system would benefit our fashion and textile supply chains and our agricultural supply chains, which are heavily intertwined with textile production. Regarding transparency, many brands are disconnected from the land where their fibres are grown, often displacing the farmer from the process (Roa, 2022). Equally, many farmers are unaware of where their fibres go once harvested. This leaves a vital connection and dialogue to be made between farmers, textile developers and brands, not only for the sake of transparency but also to establish initiatives for change and sustainable development between stakeholders.

Unless a brand knows exactly where its raw materials are coming from, they cannot conduct a full life cycle assessment or impact report or say for certain that they support the ethical treatment of farmers and livestock. Taking a regenerative approach and paying attention to the initial stages of their supply chain allows brands to understand more about their own products. How long has that raw material taken to grow or harvest? How much water, land or energy did it require? What pesticides or additional chemicals were used? How much were the farmers paid for it? All of these are necessary questions to answer in the transition to a regenerative economy. In her research for the Mistra Future Fashion programme, Goldsworthy (2017) explains that durable materials such as (recycled) polyester used in fast fashion garments create a mismatched garment/material lifespan and ultimately fail to address the wider issue of wastage in the supply chain. In their work with circular design speeds, Goldsworthy, Early et al. (2019) explore and compare different garment and textile speedcycles from ultra-fast to ultra-slow. One output of this work is the Design for Transience Framework, which highlights the importance of incorporating fast fashion solutions alongside slow fashion to create an inclusive and versatile economy.

1.1.3 An Earth-Centric Approach To Regenerative Design

Recycling requires large amounts of water and energy and typically fails to address microfibre pollution. Nevertheless, brands including Gap, Adidas, and Prada, alongside many others, choose to focus their attention on recycled plastics rather than eliminating the use of plastics altogether (Cernansky, 2022). This type of problem-solving only scratches the surface of the larger issues at hand and perpetuates a one-size-fits-all solution dominated by continued economic growth (Cobbing & Vicaire, 2017).

It could be argued that there is a lack of relevant design methodologies supporting a deeper understanding of the systems required to transform the industry (McQuillan, 2020) and that we must shift our perspectives from anthropogenic design tactics to an integrated, Earth-centric way of designing (Collet, 2022). In recognising Earth as an integrated system (Lang, Wiek et al., 2012; Schellnhuber, 1999; Steffen et al., 2005), attention is drawn to the requirement for approaches from different disciplines to tackle scientific questions regarding complex processes. In this worldview, a general goal of integration would be to "protect", "promote", and "incorporate" the diversity of languages and knowledge forms in ways relevant to sustainability in specific contexts (Lang, Wiek et al., 2012).

In this way, using regenerative design techniques can create new, Earth-centric systems that surpass circular solutions (such as textile recycling) and seek to restore the biosphere and the communities that live within it (Collet, 2022). This approach is based on the understanding that all systems are interconnected and that by designing for positive impacts on one part of the system, we can create a cascade of benefits throughout.

In creating a restorative and regenerative design methodology, we can begin to reverse the socio-ecological damage generated by the FTI, representing a fundamental paradigm shift. Rather than being anthropocentric, regenerative design promotes a holistic approach to designing for a more-than-human world (Collet, 2022) (see Figure 5).

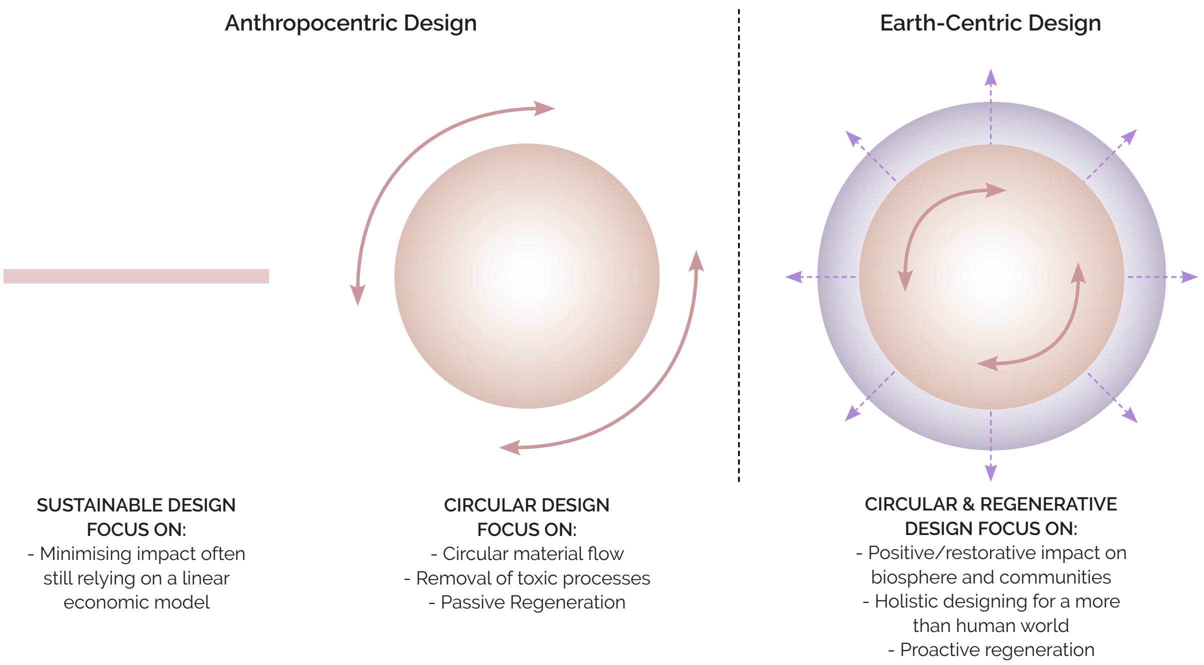


Figure 5: "Shifting creative strategies for a planetary emergence" (Collet, 2022).

Regenerated Protein Fibres

The central focus of this thesis revolves around regenerative design principles applied to regenerated protein fibres (RPFs). These RPFs, derived from food production waste streams, are abundant in protein content and have a historical precedent of being utilised for textile manufacturing, particularly during wartime and the post-war rationing period (1941–1949) in the UK and Europe. They were employed to meet the civilian demand for wool-based textiles as part of a broader strategy known as 'make do and mend.' This strategy aimed to regulate the consumption of new textile products. However, RPFs exhibited notable drawbacks in terms of durability when compared to their wool-based counterparts, contributing significantly to their eventual commercial discontinuation.

The capacity to produce RPFs from food waste, including sources like milk (casein) and nuts, has presented many opportunities to challenge existing mass manufacturing systems. In contemporary terms, RPFs are categorised as 'natural, renewable, and biodegradable' (Poole, Church et al., 2009), making them suitable for creating localised, regenerative systems that offer multiple avenues for recapturing value.

A primary goal of this research is to reassess the nexus between quality and longevity within the context of a localised and circular fashion economy. In this framework, textile quality and lifecycle analysis are aligned with the expected lifespan of the textile, garment, or product, ultimately reducing waste throughout the supply chain.

Despite exploring the concept of a disposable fashion cycle in this thesis (which may appear contradictory to most other sustainability-oriented solutions), this model has been chosen as an illustrative example to stimulate contemplation and prompt questioning of our relationships with clothing, material properties, and durability.

The Utilisation Of Alternative Waste Streams

Alongside material wastage created by the fashion industry, food waste represents a huge crisis in the modern world. It is estimated that one-third of all food produced annually globally goes to waste (Matharu, Melo et al., 2017) and that 8-10% of global greenhouse gas emissions are associated with food not consumed (UNEP, 2021). Much of this waste is lost during harvesting and production; however, an estimated 931 million tonnes of food waste are generated globally by households, restaurants, and the food service industry (UNEP, 2021).

In the UK, the dairy industry creates 20% of food waste alone (WRAP, 2016). A report written by Wrap (Fisher, Whittaker, 2018) identified that 330,000 tonnes of milk is wasted each year in the UK. Accounting for 90% of this is household waste, with the remaining 10% accounting for waste in transit and retail and waste attributed to bottling and processing. Hence, there is the potential to harmoniously address two primary waste sources (food and textiles).

Using food waste as a feedstock for novel textile fibres could reduce the waste generated by pre-consumer and post-consumer food sectors while eliminating our reliance on petrochemical-derived fibres (Stenton, Kapsali et al., 2021). Not only this, incorporating regenerative design methods and principles would ensure that materials produced are safe to manufacture and consume without further contributing to land, air, or water pollution and that the materials are biodegradable or compostable at the end of their useful lifespan.

Living System Principles

The 1987 report 'Our Common Future,' more commonly known as the Brundtland Report, laid out three fundamental components for sustainable development: environmental protection, economic growth, and social equity (Brundtland, 1987). These three facets are intrinsically interconnected and must be addressed holistically. Today, these principles are encapsulated in the Sustainable Development Goals (SDGs), a widely accepted framework for achieving sustainability across socio-economic and environmental domains. However, the measurability of these goals has faced criticism due to their broad and multifaceted nature (Swain, 2017).

Nevertheless, considering the SDGs as future scenarios to envision sustainable change offers a more comprehensive and exploratory thought process that can catalyse the development of innovative business models. A prominent illustration of this approach is presented by Raworth (2012), who utilised the SDGs as a foundation to craft an alternative economic model termed 'Doughnut Economics.' This model reimagines economic systems by advocating for a regenerative and distributive economy that respects planetary and social boundaries (Raworth, 2017).

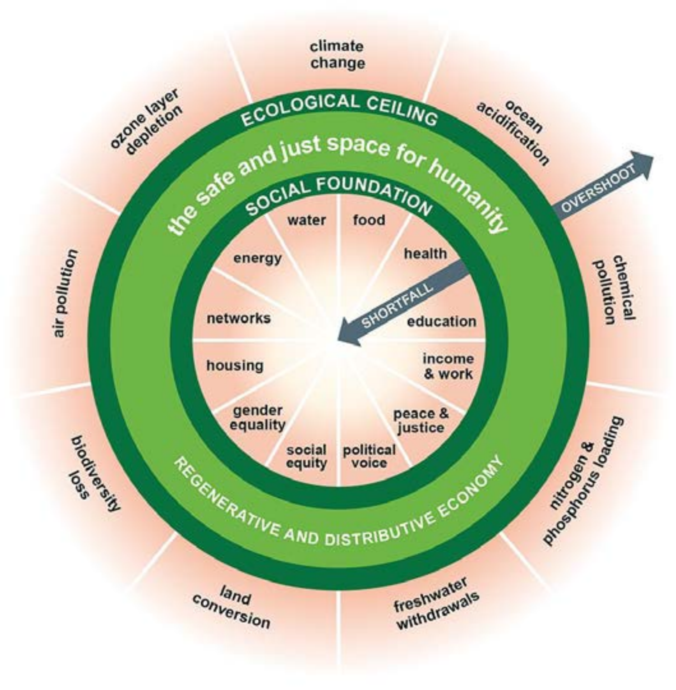


Figure 6: Doughnut Economics model depicting the safe and just space for humanity (Raworth, 2012).

This thinking aligns closely with regenerative design and has gained considerable traction in recent years, particularly within the fashion and textile sector. In the current year, the concept of Doughnut Economics has taken centre stage at various events, including the Sustainable Angle's Future Fashion Expo (The Sustainable Angle, 2022) and the British Fashion Council's Institute of Positive Fashion Forum (British Fashion Council, 2022), where Raworth served as the

Keynote Speaker. Furthermore, it has been extensively discussed by the Ellen MacArthur Foundation in multiple episodes of their Circular Economy Show podcast (MacArthur, n.d.; Raworth, n.d.).

Whal, Orr et al. (2016) argue that the establishment of regenerative cultures represents the "only viable future open to us". They draw on Reed (2007) to emphasise the importance of transitioning from simply causing less environmental harm to actively participating with the environment (Reed, 2007). Reed (2007) and Whal, Orr et al. (2016) delve into the concepts of whole systems thinking (WST) and Living System Principles (LSP) as the foundational elements for creating a regenerative culture through a fundamental shift in mindset. LSP is not a rigid set of guidelines but rather a way of thinking that frames challenges within an ecological worldview, asserting that the universe is "alive, purposeful, and evolving" (Ungard, 2005).

While this mode of thinking may appear ambiguous and open to interpretation, Irwin (2011) contends that new business models grounded in concepts such as LSP and Doughnut Economics (Raworth, 2017) can provide fresh, more sustainable solutions when applied within an ecological worldview. This necessitates the identification of all stakeholders and the resolution of conflicting needs. For designers, the core of this framework entails a shift in focus from objects to relationships, demanding a profound change in mindset (Irwin, 2012). Like the principles of Doughnut Economics, a restorative societal and environmental model would supplant the prevailing economic structure, advocating for a more respectful, ethical, and inclusive design process. Based on LSP, such a process situates problems within a larger context and involves highly collaborative, transdisciplinary teams of practitioners (Irwin, 2011).

Raworth's Doughnut Economics model posits that sustainable businesses must prioritise renewables, repair-reuse-refurbish-recycle models, modular design, and ownership to service, thus creating regenerative value chains that capture value at each stage of decomposition. This model, reminiscent of MacArthur's 'Butterfly Diagram,' divides into a biological and a technical cycle, promoting value recapture at various supply chain stages while minimising loss of matter and energy. Shifting the focus toward developing healthier biological systems that enrich our environment and safeguard biodiversity is pivotal in mitigating the effects of climate change. This concept of material recovery situates decomposition at the intersection of biology and systems thinking, framing it as a crucial means of recapturing value alongside the more commonly explored methods of repair, reuse, and recycle. This aspect of LSP has ignited a renewed interest in regenerative design practices within the fashion industry, bridging regenerative agriculture with textile processing and garment production.

1.2 Research Question

The starting point for this project was to investigate local food waste streams as a material resource for the fashion industry. As a fashion and textile designer, my task was to find alternative and sustainable ways to process these waste steams into such material while considering textile composition, manufacturing methods and colouration techniques. Using historical literature and patents was essential to understanding an existing yet primarily overlooked group of textile materials, namely, RPFs and their subsequent manufacturing methods. Based on these early criteria, the original question set by the BFTT for WP6 was:

Can local pre-consumer food and agricultural waste streams become sustainable feedstock for localised fibre and sheet material production?

This was quite a broad starting point for a research question. As the research developed, the question evolved and became more focused. Early on, the primary source of pre-consumer food and agricultural waste to be used was defined as casein. This was due to casein being both a significant waste generator and a readily available source of food industry waste in the UK (WRAP, n.d.), alongside ease of availability for exploration in various forms (milk, powder, fibres, yarn and fabric) throughout the project.

A deeper investigation into historical manufacturing methods and applications for casein-based materials was conducted. Information uncovered during this stage led to an enhanced understanding of the anthropological associations between materiality and society, causing me to question our current fashion and textile needs alongside our planetary boundaries through a systems-thinking perspective. As the research progressed through experimentation and material testing, it became evident that creating novel materials alone was not enough; the research must also consider new ways of thinking that support these localised and alternative practices. Definitions for terminology surrounding 'quality', 'disposability', 'slow' and 'fast' were also challenged, contributing to the final research question:

How can transdisciplinary collaboration between green chemistry and textile practices advance the understanding and utilisation of casein-based materials in regenerative fashion while challenging prevailing notions of disposability as an indicator of quality*?

Although the question has evolved in response to the research, the original question set by the BFTT has still been addressed through the consideration of 'local pre-consumer food and agricultural waste streams', which continued to be a central theme throughout the project.

1.3 Aims And Objectives

Aims:

1. To advance the understanding of casein fibre processing for its integration into a regenerative fashion economy through knowledge integration.

2. To establish an effective transdisciplinary methodology encompassing design, green chemistry, and archive data, facilitating the generation of novel insights in processing casein for regenerative textiles.

3. Critically examine and evaluate prevailing perceptions of regenerative principles and disposability as quality indicators within the fashion industry.

Objectives:

1. To document contemporary and historical textile practices concerning regenerated casein fibres and other protein-based textile materials, delineating the techniques employed and the resources utilised.

2. To map the origins and implications of disposability within the context of speedcycles and offer a multidimensional perspective on this phenomenon.

3. To undertake a thorough critical review of casein-based materials within a regenerative design framework, incorporating Living System Principles (LSP).

4. To leverage insights gained through the transdisciplinary process to guide the design and fabrication of textile artefacts that exemplify casein materials' aesthetic and functional characteristics within regenerative fast fashion.

5. Engage with stakeholders to understand preconceptions of garment quality and critically evaluate 'the vision'.

6. To engage in a comprehensive critical reflection, drawing upon the outcomes of the evaluation process and findings, thus contributing to the ongoing discourse in regenerative design.

AIM	OBJECTIVE	CHAPTER
AIM 1. To advance the understanding of casein fibre processing for its integration into a regenerative fashion economy through knowledge integration.	1. To document contemporary and historical textile practices concerning regenerated casein fibres and other protein-based textile materials, delineating the techniques employed and the resources utilised. 2. To map the origins and implications of disposability within the context of speedcycles and offer a multidimensional perspective on this phenomenon.	2. Informing Contemporary Practice with Historical 2. Informing Contemporary Practice with Historical
AIM 2. To establish an effective transdisciplinary methodology encompassing design, green chemistry, and archive data facilitating the generation of novel insights in processing casein for regenerative textiles.	3. To undertake a thorough critical review of casein-based materials within a regenerative design framework, incorporating principles from Living System Principles (LSP). 4. To leverage insights gained through the transdisciplinary process to guide the design and fabrication of textile artefacts that exemplify casein materials' aesthetic and functional characteristics within regenerative fast fashion.	5. Practice 1: Exploration of Casein-Based Materials and Colour 3. Methodology 6. Practice 2: Regenerative Design Thinking for Transient Casein-Based Garments
AIM 3. Critically examine and evaluate prevailing perceptions of regenerative principles and disposability as quality indicators within the fashion industry.	5. Engage with stakeholders to understand preconceptions of garment quality and critically evaluate 'the vision'. 6. To engage in a comprehensive critical reflection, drawing upon the outcomes of the evaluation process and findings, thus contributing to the ongoing discourse in regenerative design.	4. Understanding Perceptions of Garment Quality 7. Answering the Research Question 8. Conclusion

Figure 7: Research aims and objectives

Figure 7 demonstrates how the research aims and objectives are met within each chapter. Although the objectives have been presented linearly, some objectives were answered through multiple chapters and were not necessarily answered in chronological order. Many of the objectives overlap with others and are revisited throughout the research. For example, Chapter 5, Practice 1: Exploration of casein-based materials and colour, is presented under Objective 3 as a part of the critical review of casein-based materials within a regenerative fashion economy; however, it could also have been placed under Objective 4, reflecting the transdisciplinary process.

1.4 Original Contribution To Knowledge

This thesis argues two key contributions to knowledge presented throughout the research. The first is a transdisciplinary methodology between the designer, chemist, and historian, allowing for genuine knowledge exchange and collaboration of equal merit. The second contribution is a design framework for a localised, regenerative fashion system that uses a fourth generation of green casein fibres. This second contribution presents new discourse and a new perspective on textile quality, disposability, and casein fibres.

Within these original contributions to knowledge, a case study for the sustainable colouration of casein-based materials using anthocyanins extracted from food waste is used as proof of concept for one of many potential further outcomes. This proof of concept directly results from the first and second contributions combined. Only by building the transdisciplinary methodology and regenerative design framework (RDF) was the subsequent work into anthocyanins extracted from food waste possible, thus exemplifying their success in the field.

1.4.1 Contribution One: Transdisciplinary Methodology

This research outlines a new transdisciplinary methodology. Using an iterative process, the methodology offers researchers and industry practitioners a process for *genuine* knowledge exchange, collaboration, and integration of different disciplinary practices in a creative and explorative way. Here, '*genuine*' refers to creating respectful, equal, and open relationships between researchers, practitioners, and disciplines. Developing these relationships requires time and effort to form an agreed-upon understanding of the research problem, aims and objectives and should not be clouded by meritocracy.

The concept of a transdisciplinary methodology is introduced in Chapter 3 alongside the regenerative design framework and methodology. Three key stages of Explore, Experiment and Evaluate are outlined in Section 3.4 and are used continuously throughout the research. These stages are not isolated within the transdisciplinary methodology but fit harmoniously within the RDF. Ten different methods were used to best conduct this research in line with the objectives: Literature review, collaborative learning, visual thinking, creative play, experimental design, lab visits, interviews, consumer survey, presentations, and material testing.

1.4.2 Contribution Two: Regenerative Design Framework

This research introduces an RDF for application across industry, academia, and design practice. The fashion and textile design process within this framework draws upon Goldsworthy's exploration of speedcycles (2017) and is informed by historical methods adept at aligning material properties with garment lifespan. This contribution provided three additional insights, offering fresh perspectives on textile quality, disposability, and the fourth generation of casein fibres developed through green chemistry.

A new lens on Textile Quality
This research advocates for a novel interpretation of textile quality, shifting the emphasis from the user stage to the end of a garment's life. Building upon Goldsworthy's examination of speedcycles, particularly in the context of fast fashion, there arises an opportunity to explore trend-driven garments intentionally designed to last for a specific number of wears yet remain user-friendly for responsible disposal.

A new lens on Disposability
In tandem with this revaluation of textile quality, a new discourse on disposability arises. Proposing that disposability can be regarded as a textile quality challenges the prevailing notion that slow fashion is better regarding both environment and quality. Instead, it invites consideration of how we, as a society, presently engage with garments, whether for short-term or long-term use.

A new lens on Casein Fibres
This reframing of quality and disposability offers a new perspective on casein, portraying it as a naturally compostable material rich in nutrients but with lower strength properties. These characteristics position casein as a distinctive example of a regenerative, mono-material archetype. Within this paradigm, textile fabric, components, and coatings all originate from the same raw material. While casein-based materials have been subject to exploration throughout history (2.2.1), never have they been integrated in a manner that allows for a fully compostable or intentionally disposable garment archetype.

1.5 Chapter Outline

The eight chapters of this thesis follow the transdisciplinary journey undertaken throughout the PhD. Information uncovered in the literature during the early stages of this project has influenced the experimentation and practice throughout the duration of the PhD. Although the thesis has been written in a linear format, the learning process has been iterative, exchanging knowledge and ideas back and forth between project partners through each stage of the research.

Chapter 1: Introduces the wider context of the research and its urgency. The research question aims and objectives, and the original contributions to knowledge are outlined here.

Chapter 2: Explores the historical significance of RPFs in the context of evolving social developments and cultural attitudes, linking them to contemporary environmental issues and design practices.

Chapter 3: Outlines the development of the integrated methodological framework based on gaps in knowledge in the existing literature.

Chapter 4: Presents consumer survey results and disseminates participants' responses in line with the development of a speculative future vision.

Chapter 5: Documents the exploration of casein-based materials and colour through transdisciplinary experimentation. Material testing related to the RDF is also documented here.

Chapter 6: Continues to build upon the RDF through the final brief, documenting the design of Transient, casein-based garments (TCGs).

Chapter 7: Presents how the experimental, methodological, and technical findings helped to answer the research question. The key questions identified at the end of Chapter Two (2.5) are revisited and evaluated in terms of how successfully gaps in knowledge have been addressed.

Chapter 8: Outlines how each objective has been met and summarises the contributions to knowledge. Key achievements of the project and proof of concepts for future research are identified.

2

INFORMING CONTEMPORARY PRACTICE WITH HISTORICAL RESEARCH

In this chapter, an exploration of historical journals, patents, and museum archives (in collaboration with the V&A) has been used to understand the circumstances for both the uprising and downfall of casein materials between the 1930s and 1950s. The historical significance of casein and the technology required to manufacture such materials are explored.

Moving into a post-war era, this chapter also investigates the beginning of throwaway culture as an expression of a new, carefree lifestyle. Early and contemporary examples of fast fashion and the environmental and social impact of a disposable way of life are discussed. Concepts and terminology surrounding regenerative systems are then contextualised in relation to the research question and project brief. Finally, gaps in knowledge within the literature discussed are identified, providing context for the research question and identifying key stakeholders and possible areas for intervention.

2.1 Chapter Framework And Breakdown

This chapter is framed around four major co-authored, peer-reviewed papers published throughout the PhD.

> From Clothing Rations to Fast Fashion: Utilising Regenerated Protein Fibres to Alleviate Pressures on Mass Production, (Stenton, Kapsali et al., 2021),
>
> The Potential for Regenerated Protein Fibres within a Circular Economy: Lessons from the Past Can Inform Sustainable Innovation in the Textiles Industry (Stenton, Houghton et al., 2021),
>
> Referencing Historical Practices and Emergent Technologies in the Future Develop ment of a Sustainable Textile Sector: A Case Study Exploring 'Ardil' a UK-Based Regenerated Protein Fibre (Auerbach George, Stenton et al., 2022)
>
> Challenging speed cycles in contemporary fashion: A review of the paper dresses trend in the UK and the USA during the 1960s (Auerbach George, Tregenza et al., 2023).

Each of these papers has contributed to this chapter through extensive data analysis, which helped to structure the literature review of this thesis. Conclusions drawn from each paper helped set the initial parameters for the practice-based research by identifying gaps in knowledge early in the project.

Early on, rubbish theory (Thompson, 2017) was identified as a framework for comparing cross-generational factors, including technological developments, social and political circumstances, and consumer mindsets. These key topics were continuously drawn upon throughout the thesis and helped structure the literature review. The sub-sections of this chapter are then introduced, linking them back to the core aims and objectives of the research.

2.1.1 Exploring Changing Attitudes Through Rubbish Theory

Evolving perspectives on the value of specific fashions, textiles, and technologies. Initially conceived by Thompson in 1979, this concept delves into the notion that 'value is not a fixed characteristic and cannot be created without at the same time creating non-value' (Thompson, 2017). Products are categorised into two realms: transient and durable, asserting that societal perceptions assign these categories, reflecting a shared worldview. Transient items lose value over time and possess finite expected lifespans, ultimately becoming waste, whereas durable items gain value and maintain indefinite lifespans (Thompson, 2017).

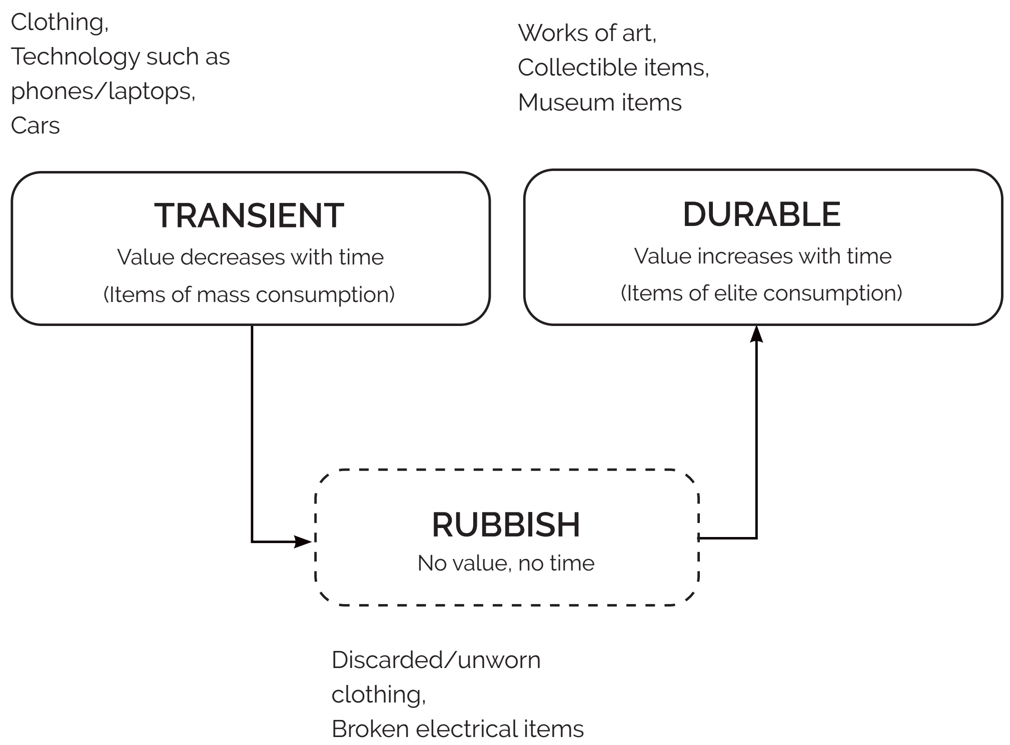


Figure 8: Rubbish Theory hypothesis (Thompson, 2017).

Thompson contends that the value of transient items naturally diminishes until it reaches zero, emphasising the pivotal role of the 'rubbish' phase in the revaluation process. As a textile conservation specialist specialising in RPFs, Brooks asserts that the changing status of RPFs aligns with the rubbish theory cycle (Brooks & Rose, 2006). By examining archive data, historical journals, and patents, Brooks and Rose scrutinise why and when RPFs have gained or lost favour with governments and consumers. They identify three possible RPF generations: the first, crafted between 1894 and 1905; the second, between 1920 and the 1960s; and a third, brief resurgence in the 1970s.

The literature review adopts a holistic perspective by mapping historical challenges from an economic, environmental, and societal perspective alongside social and political shifts and advancements in fibre technology. These historical insights can then be reframed into present-day opportunities for addressing contemporary issues. This approach fosters a more comprehensive and inclusive manner of contemplating design's enduring impact on the environment and society through the lens of rubbish theory.

Informed by Thompson's rubbish theory and Brooks' fibre generations, this timeline (Figure 9) highlights pivotal events influencing our fashion consumption choices, revealing changing interests in different fibre types transitioning from natural to synthetic. Although synthetic fibres trace their origins to 1855 (Audemars, 1855), this timeline commences in 1894 with the experimentation involving various protein fibres, later categorised as RPFs. Each key event and technological advancement presented on the timeline guides the organisation of information into three core subsections: 'Materials from Milk' (Objective 1), 'Disposability vs. Durability' (Objective 2), and 'Transitioning to a Regenerative Economy' (Objective 3).

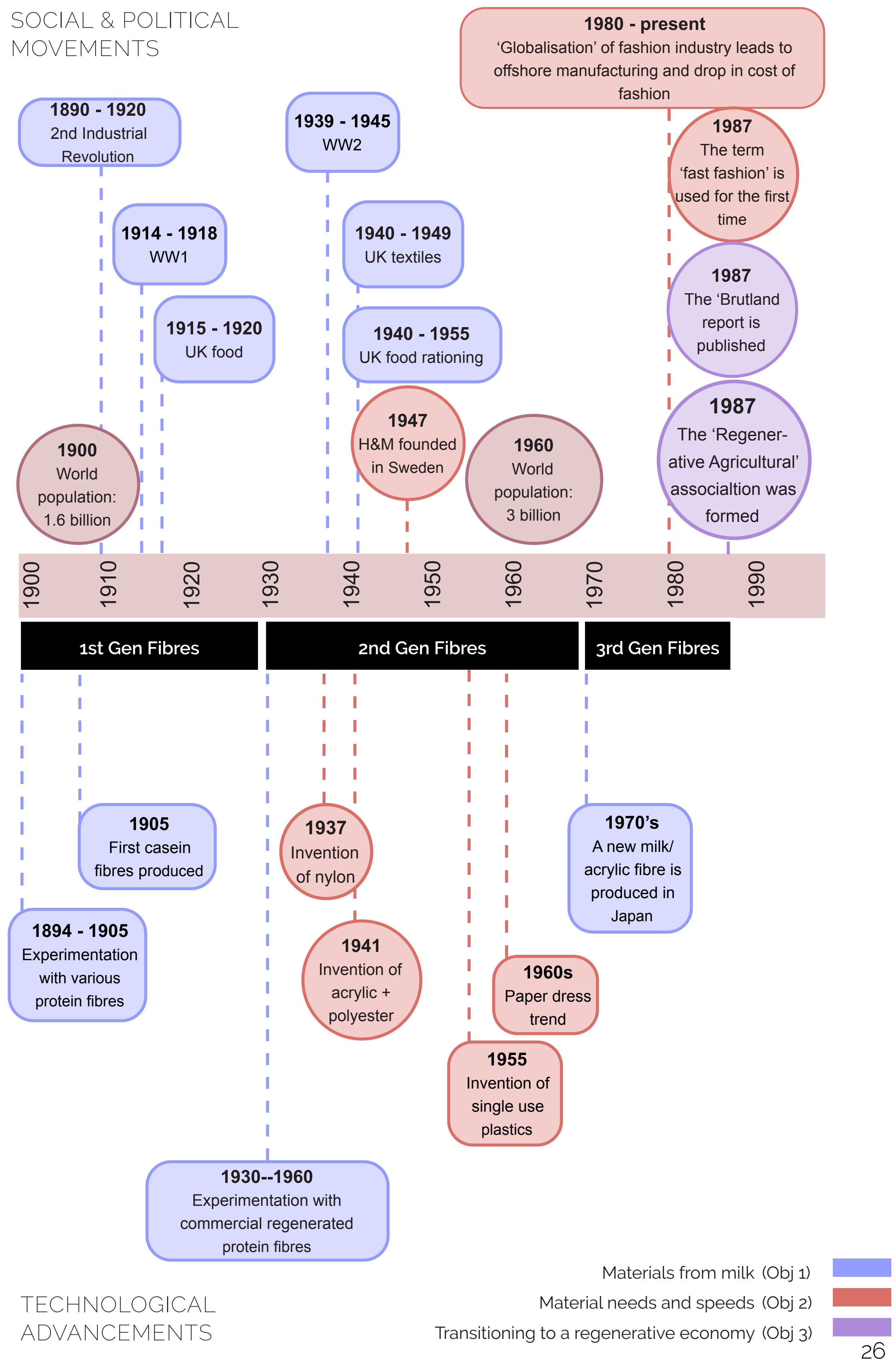


Figure 9: This figure is a recreation of the timeline created for the publication 'The Potential for Regenerated Protein Fibres within a Circular Economy: Lessons from the Past Can Inform Sustainable Innovation in the Textiles Industry' (Stenton, Kapsali et al., 2021) and has been updated to include the introduction of single-use plastics and the paper dresses trend (2.3.1). Each event has been colour coordinated against each sub-section of this chapter (not including 'gaps in knowledge' or 'the summary') and which objective it fulfils.

2.2 Materials From Milk

This section responds to objective one by exploring the historical significance of materials created from milk during the First and Second World Wars as a response to material shortages and hardship. As well as textile fibres, galalith (a casein-based bioplastic) is also drawn upon in terms of cultural relevance. The social and political responses to past circumstances have been used to draw parallels between a time of deprivation and our current issue of overconsumption and stretched natural resources.

2.2.1 Origins Of Materials From Milk

The Industrial Revolution, World War I (WWI), and the impact of globalisation had significant implications for the evolution of Regenerated Protein Fibres (RPFs). During WWI, numerous household items were substituted with alternatives referred to as 'ersatz,' a term borrowed from German, denoting wartime scarcity. In contrast to regenerated cellulose fibres like rayon, invented approximately 25 years before WWI (Hosch n.d.), RPFs were initially conceived as ersatz around WWI but met with limited success. These first-generation fibres suffered from poor strength and never reached the necessary level of development for commercial viability (Sadtler 1925). By the 1920s, industrial efforts in this direction had largely been abandoned.

During WWII, the development of experimental textile fibres regained momentum. Since petrochemical-based synthetics had yet to penetrate the domestic textile market, wool was used for uniforms and equipment, leading to shortages in civilian textiles. At this time, roughly 65% of the textile industry's production capacity was dedicated to government fabrics (Heard, 1942), and wool for uniforms was considered as crucial as ammunition (O'Brien, 1942).

Textile manufacturers increasingly recognised the impact of war on fibre supplies and changing consumer demands, sparking a global race to achieve technical progress in producing alternative and localised fibres (Brooks & Rose, 2006). Mcfarlane (1953) noted, "Every country worldwide aimed to make its textile industry self-sufficient by utilising locally available resources." Responding to the same needs as first-generation RPFs, these second-generation RPFs achieved much greater commercial viability. They were often blended with traditional fibres like wool to enhance material properties and prolong reserves.

One of the most extensively explored and versatile RPFs during this period was casein, a protein in milk and dairy products. Due to shortages of non-textile materials such as glass and metal during WWII, synthetic alternatives once again became a priority. Early plastic production in the USA surged by 300% (Nicholson, Leighton 1942, Zaman, Ahsan 2020). Besides textile fibres, casein could be transformed into a plastic-like substance known as Galalith (Erinoid in the UK).

While plastic widely replaced aircraft windows and even steel in automobiles, Galalith was often employed for smaller components and gained popularity as an alternative for buttons and jewellery. Casein buttons were commercially produced as early as 1910 in the UK, and although demand increased significantly during both world wars, production finally ceased in the 1970s (Codelite, n.d.).

Following the war, the reputation of RPFs quickly dwindled. Escalating raw material costs and ongoing technical challenges (Coleman, 1969) were met with a new array of synthetic fibres that thrived in areas where RPFs had repeatedly fallen short. Petrochemical-based fibres such as Nylon, Polyester, and acrylic exhibited superior durability, higher tensile strength, and easier maintenance than RPFs, ensuring a more consistent supply of materials (Poole, Church et al., 2009).

By 1955, the total output of RPFs had fallen below half that of synthetics (Hauge, 1958). Alongside competition from emerging fossil fuel-derived materials, the rayon industry also expanded. Innovations in crease-resistant finishing for rayon, coupled with enhancements in its wet and dry strength, propelled rayon ahead of RPFs in terms of popularity (Hard, 1939). In the USA, the production of cellulosic fibres surged from nearly 16,000 tonnes in 1923 to almost 6 million tonnes in 1951. In contrast, the production of all other synthetic fibres at the time was approximately 95,000 tonnes (McFarlane, 1953). During this period, synthetic fibres of all kinds transitioned from luxurious novelties to affordable and practical products, while the production of RPFs ceased entirely by 1960.

The third generation of RPFs emerged in response to advancements in textile technology and biotechnology and a growing demand for fibres with reduced environmental impact. This renewed interest in technologically advanced yet eco-friendly textiles prompted the exploration of alternative raw materials (Brooks, 2009). Consequently, a new milk and acrylic blended fibre known as Chinon was introduced in Japan during the 1970s. These fibres were described as hygienic, smooth, renewable, and biodegradable (Chauahn, Arya et al., 2018). However, they also faced challenges related to low durability and high production costs (Kiplinger, 2003), leading to the swift discontinuation of Chinon production with little historical record left behind.

2.2.2 Technologies And Manufacturing

Between 1896 and 1963, 146 patents related to protein-based fibre production were filed, with the majority occurring in the 1930s and 1940s (Brooks, 2014). The first recorded patent for this type of fibre dates to 1894, credited to Adam Millar. Millar's patent involved the creation of gelatine filaments by extruding a concentrated, hot gelatine solution through nozzles to form fine threads. These threads, known as Vanduara silk, were wound on revolving cylinders and left to dry for weaving. Despite being highly promoted, they proved unsuitable for commercial use due to their weak strength and water absorption (Millar, 1894).

During WWII, the technology for producing RPFs underwent significant changes, primarily focused on improving the fibres' functional properties rather than streamlining the manufacturing process. The extensive number of patents filed during this period, aiming to enhance RPFs' wet strength, underscores the persistent challenge (Brooks, 2014).

In the 1940s, the production of casein-based fibres involved using several undesirable and potentially harmful chemicals. Notably, formaldehyde, a naturally occurring organic compound (CH2O), was used as a cross-linking agent to increase the fibres' dry and wet tenacity (Bier, Kohn et al. 2017). Today, formaldehyde is recognised for its safety concerns, including acute toxicity, suspected carcinogenicity, and mutagenicity (Formaldehyde and Cancer Risk. 2011). Consequently, its use and disposal are subject to stricter regulations. Additionally, the coagulation and hardening baths employed high concentrations of sulphuric acid and metallic salts, leading to issues with waste treatment and concerns regarding worker health and safety.

Converting milk waste into textile fibre or monofilament involves several steps and processes. The process starts with collecting and preparing milk waste, which is separated from contaminants like fats, water, and lactose to isolate the casein. Next, an acid (generally a lactic acid or citric acid) is added to the milk waste, causing it to curdle. The casein is then separated from the liquid whey through filtration or centrifugation. The separated casein is washed and purified to remove any remaining impurities. After purification, the casein is dissolved in an alkaline solution, often with sodium hydroxide (caustic soda). This solution produces a viscous, homogeneous liquid that can be extruded through fine nozzles to create continuous fibres or monofilaments. Once extruded, the casein filaments are passed through a bath containing a coagulating agent (usually formaldehyde). The coagulation bath solidifies the casein, transforming it from a liquid state into a solid fibre or monofilament. The formed fibres are dried and processed further to enhance their properties. The resulting casein fibres or monofilaments can be woven, knitted, or blended with other natural or synthetic fibres to create textiles and fabrics.

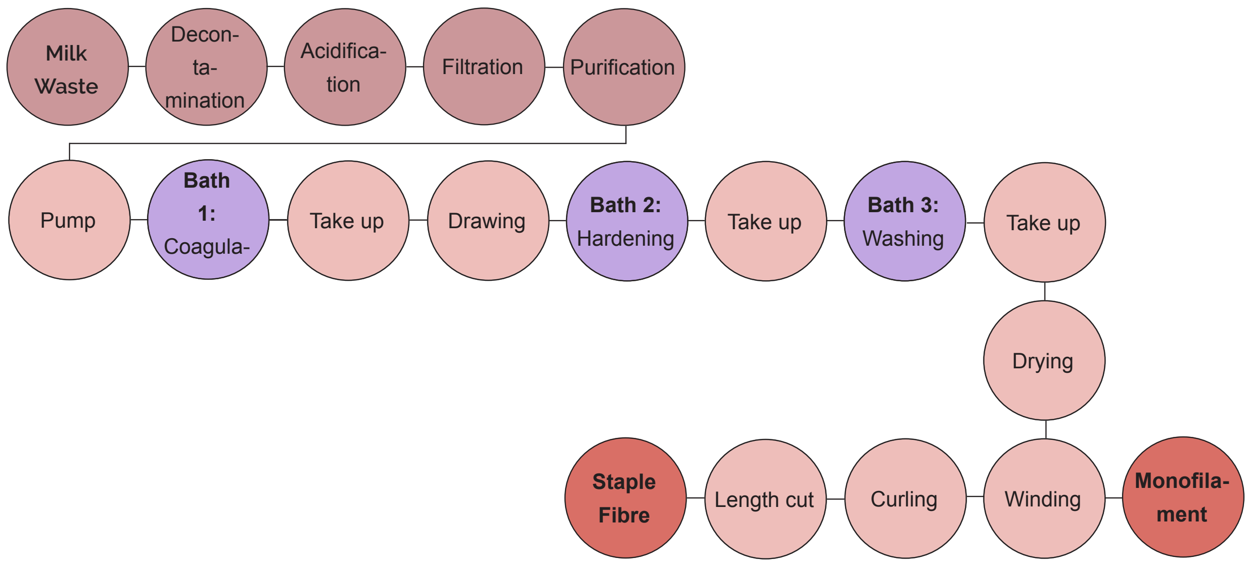


Figure 10: Basic process of converting milk waste into a textile fibre or monofilament.

Today, a limited range of casein-based materials are available commercially, mainly on craft-based websites catering to knitters and weavers in the USA. However, the manufacturing process and the presence of formaldehyde in these materials remain unclear. To address the growing demand for ecologically produced textiles, Italian spinner Filati Maclodio introduced a line of milk-blended yarns called Milkofil in 2007 (Singleton, 2008). These yarns were known for their light, silky weave, breathability, promotion of blood circulation, and natural antibacterial properties. Typically, they contain 35-70% casein and can be blended with natural fibres like silk, cotton, cashmere, and linen (Smith, 2009).

Subsequently, in 2010, the German company QMILK developed a high-quality, organic textile fibre derived from milk waste using electrospinning. This fourth-generation RPF is free from harmful additive chemicals and produces a biopolymer fibre suitable for various applications, including fashion (WRAP, n.d.).

In addition to textile fibres, UK-based button manufacturer Courtney & Co revived the production of casein buttons in 2015, 45 years after their initial discontinuation in the UK. These buttons, branded as Codelite, are created by adding rennet to milk to separate solid curds from the liquid. A solution containing low concentrations of formaldehyde, known as formalin, is then added to transform the curd into a solid material. The result is a durable and versatile material that can be dyed and polished to achieve different finishes. Despite the inclusion of formalin, the manufacturing process prioritises sustainability and traceability, with the buttons certified as biodegradable (see appendix 10.1.2).

While Brooks identifies only three generations of RPFs, the materials discussed here represent the foundation of a fourth generation of environmentally conscious RPFs. These modern casein-based examples illustrate how historical technologies can be redeveloped with a sustainability focus to meet current needs. This concept has been built upon throughout the research and is further discussed in Section 2.4 (p48).

2.2.3 Challenges And Opportunities

Although WWII ended in 1945, textile rationing persisted until 1949. During this period, extensive efforts were made to promote RPFs, primarily due to the substantial investments made by companies and governments during the war (Cook, 1984). RPFs were vigorously advertised and embraced as "wonder fibres," with home and fashion magazines depicting them as patriotic choices that supported the war effort. An editorial in Harper's Bazaar, an American fashion magazine from August 1946, exemplified this marketing strategy, linking RPFs to patriotism: "Now we will wear milk - dress in new milk-fed clothes based on discoveries that are rocking the fabric industry and taking the sting out of wool shortages" (Harper's Bazaar, 1946).

However, as the new decade dawned, petrochemical-based synthetics gained popularity and were promoted as the textiles of a carefree, modern world. In contrast, RPFs were considered inferior substitute fibres associated with deprivation and hardship. This shift in public perception reflected changing cultural values in fashion and clothing. According to Brooks and Rose (2006), this change in the status of RPFs aligns with the cycle of Rubbish Theory (Thompson, 2017), serving as a response to new materials and cultural values. The cycle of rubbish theory can be illustrated in terms of the challenges and opportunities facing RPFs. Initially, food waste and raw materials, considered rubbish, were transformed into new materials through technological advancements and government support, with marketing strategies reinforcing positive cultural associations during times of crisis (opportunity).

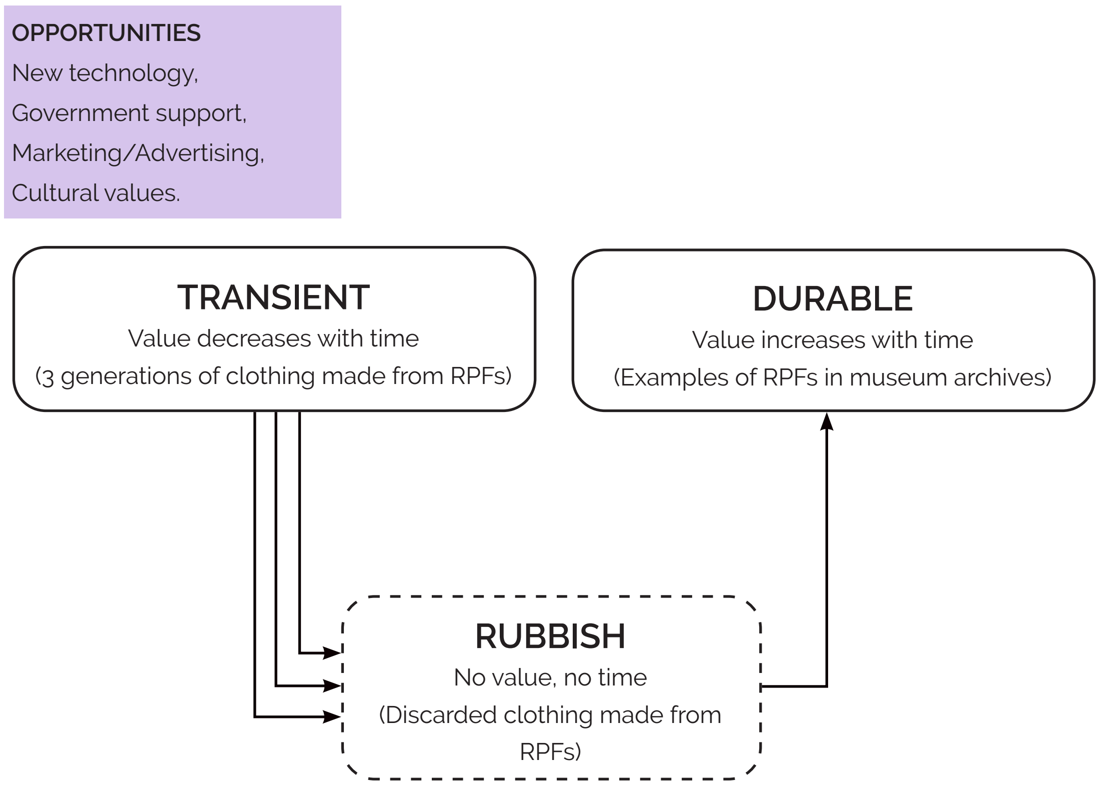


Figure 11: Responding to opportunities - The Rubbish Theory hypothesis exemplifies how three generations of RPFs were created in response to external opportunities.

Like other material objects and clothing (excluding couture and high-fashion items), RPFs were initially produced in a transient state where their value could only diminish over time. Competition from other materials and changing consumer attitudes rendered RPFs obsolete, causing them to decline to a lower social status (challenge), eventually becoming regarded as rubbish. A few RPF examples, however, transitioned to a durable state, with some preserved in museum collections or as collectable pieces. This cycle repeated several times, resulting in multiple generations of RPFs developed in response to new technological advancements and societal needs.

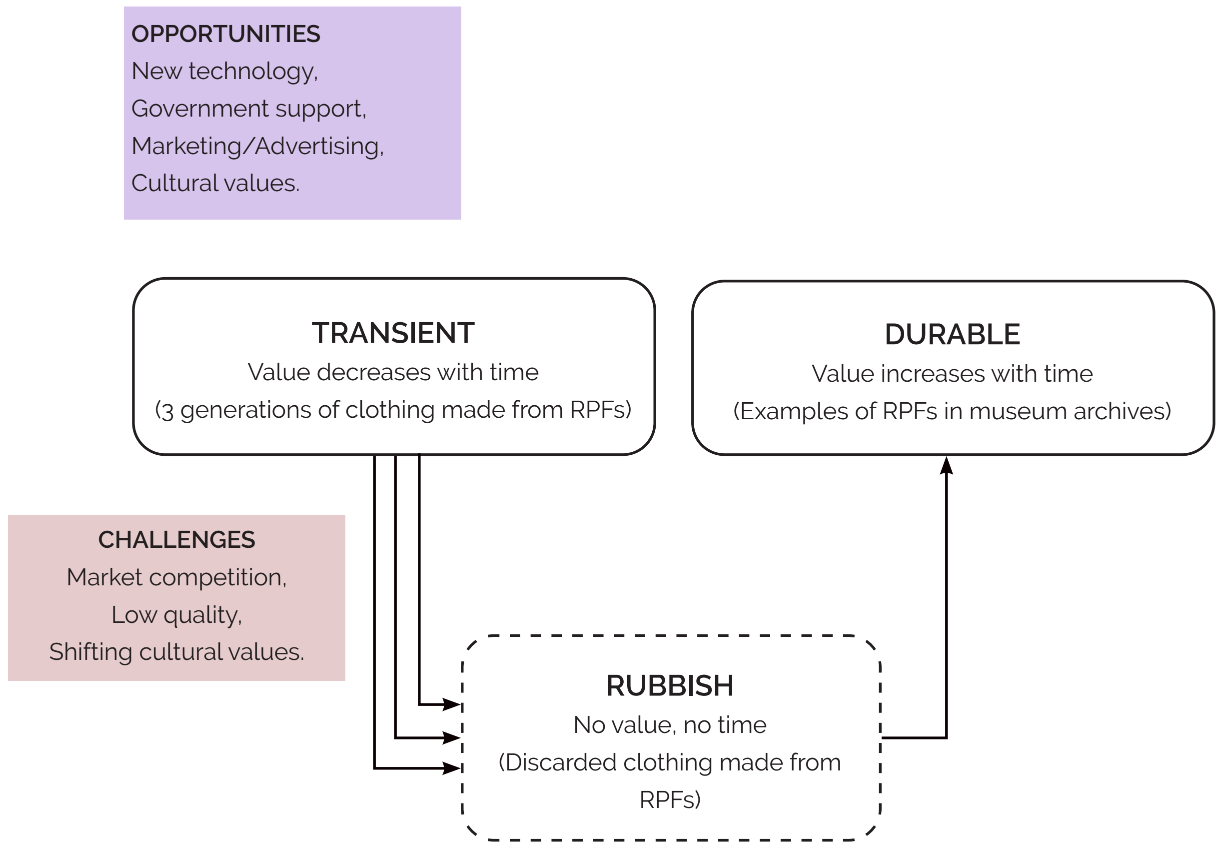
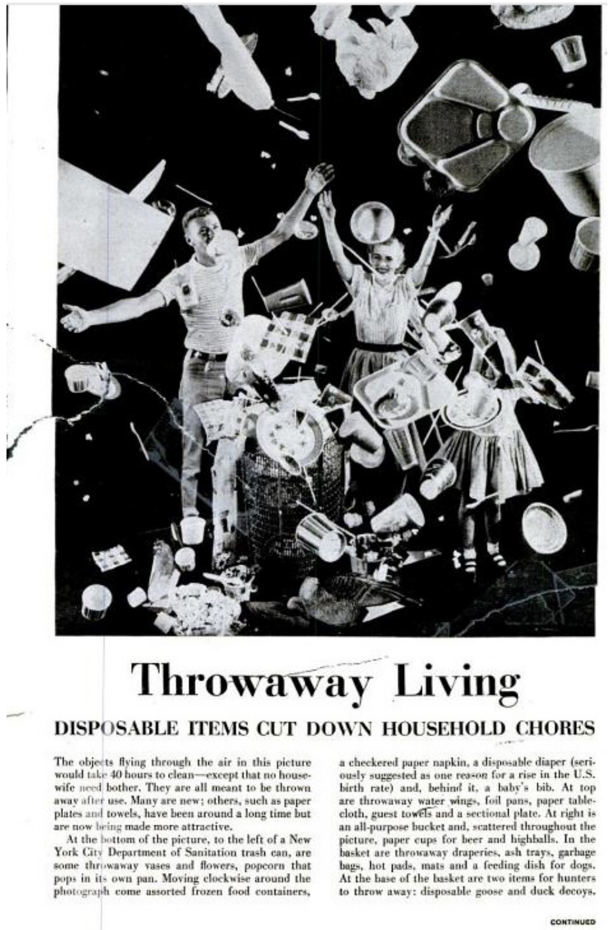


Figure 12: Facing challenges - Rubbish Theory hypothesis exemplifying the transition of RPFs from transient to rubbish. (Thompson, 2017).

2.3 Disposability Vs Durability

This section responds to Objective Two, following the fashion industry's growth and tracing its environmental impact in relation to a growing population and dwindling natural resources. An anthropological and human-centred approach has been taken to understand the development leading to increased seasonal collections and low prices as well as the inevitable environmental consequences. Within this approach, consumer preconceptions surrounding fashion and durability have been explored following the concept of rubbish theory.

Stemming from the hardship of WWII and textile rationing, the 1960s offered a unique perspective on how social circumstances can alter consumer mindsets and encourage shifts in cultural attitudes. For this thesis, a short-lived trend of garments made from paper during the 1960s has been identified as a pivotal moment in fashion where the explicit 'disposability' of garments is encouraged for the first time.



Throwaway Living

DISPOSABLE ITEMS CUT DOWN HOUSEHOLD CHORES

The objects flying through the air in this picture would take 40 hours to clean—except that no housewife need bother. They are all meant to be thrown away after use. Many are new; others, such as paper plates and towels, have been around a long time but are now being made more attractive.

At the bottom of the picture, to the left of a New York City Department of Sanitation trash can, are some throwaway vases and flowers, popcorn that pops in its own pan. Moving clockwise around the photograph come assorted frozen food containers, a checkered paper napkin, a disposable diaper (seriously suggested as one reason for a rise in the U.S. birth rate) and, behind it, a baby's bib. At top are throwaway water wings, foil pans, paper tablecloth, guest towels and a sectional plate. At right is an all-purpose bucket and, scattered throughout the picture, paper cups for beer and highballs. In the basket are throwaway draperies, ash trays, garbage bags, hot pads, mats and a feeding dish for dogs. At the base of the basket are two items for hunters to throw away: disposable goose and duck decoys.

CONTINUED

Figure 13: Throwaway Living article, Life Magazine, 1955.

Figure 14: 'Dixie Cup Dispenser' advertisement, 1954.

2.3.1 The Origins Of Throwaway Culture

The term "fast fashion" originated in a 1989 New York Times article to describe Zara, a fashion retailer. Juan Lopez, Zara's USA head of operations, emphasized their rapid fashion turnover, with new shipments from Spain every week and a mere 15-day turnaround from idea to store (Schiro, 1989). Zara, an established Spanish brand for 15 years, was a pioneer of fast fashion, along with H&M, founded in Sweden in 1947 (Idacavage, 2018).

In the post-war 1960s, priorities for businesses and consumers shifted once more. The advent of affordable, mass-produced plastics ushered in the concept of "Throwaway living," as showcased in a 1955 Life Magazine article aiming to alleviate housewives' daily chores like dishwashing (Cosgrove, 2014). Plastics soon infiltrated various aspects of everyday life, from packaging to clothing, construction (Zaman & Newman, 2021), and the automotive industry (Zaman & Ahsan, 2020).

This new mass manufacturing approach was initially introduced to stimulate job creation and rejuvenate the global economy after the Great Depression and WWII (Zaman & Ahsan, 2020). However, it evolved to encourage customers to repeatedly buy similar or identical products within a short timeframe, known as "planned obsolescence," with unintended consequences (Zaman & Ahsan, 2020). As many aspects of life shifted towards disposable items, fashion advertisements prioritized price and aesthetics over fibre quality and functionality. Brands flooded the market with more styles and collections per year, relying heavily on oil-based fibres like polyester and nylon (Smelik, 2023), as illustrated in Figure 15 with the headline "A million dollars' worth of cool for only a few bucks."

Dependence on cheap, low-quality fibres, especially in the fast fashion sector, neglected consumer education about fibres. During this period, the domestic textile market dwindled significantly. Why make your own clothes when you can buy them cheaper (Stenton, Kapsali et al., 2021)? As the younger generation rejected their parents' sartorial traditions, a perpetual demand for affordable new clothing emerged. To keep up, American and European companies relocated their factories to developing countries, saving millions through labour outsourcing (Maxwell, 2014).

Figure 15: Campus Add circa 1960-1970.

Paper Dresses

Early offshoring practices aligned with the globalizing agenda of the time. In the mid-1960s, the rapid emergence of new trends coincided with the rise of popular culture in film and music and a wave of social and political movements. The Civil Rights Act, anti-war protests, and the women's liberation movement profoundly influenced public perceptions and consumer habits once again (Hilton 2007, Brownstein 2020). Fashion and politics were intertwined during this period (Vargas, 2006), with women at the forefront. Debates surrounding motherhood, lifestyle, work, and fashion (Brown, 2012) offered a sense of freedom and revolution. Alongside an appetite for fun and rapidly changing fashion, this paved the way for a trend of disposable paper dresses designed for single-time wear (Paper Dresses, n.d.).

Mass-produced paper dresses initially served as a promotional tool by Scott Paper in America 1966. Constructed from Dura-Weave, a cellulose-based material used for disposable hospital gowns, these dresses featured bright colours and bold, iconic prints. Other companies and artists, including Andy Warhol, recognized the potential of these promotional garments. Warhol designed his range of paper dresses featuring his iconic artworks (Lyons, 2014).

Figure 16: Hallmark Flower fantasy Paper Dress Ad, 1967.

Figure 17: "Nixon Girls," in Nixon dresses lining an aisle at the Civic Arena to greet Nixon on his arrival to the rally, Oct. 28, 1968.

Eventually, more durable materials, combining wood pulp and synthetic fibres, were used to produce these 'paper' dresses. This paper-like material required minimal maintenance and could be refreshed with a cool iron (Lyons, 2014). Between 1966 and 1968, over one million paper dresses were sold (Pulp Fashion: Paper Dresses of the 1960s, 2020). While some saw disposable fashion as the future, others found it impractical and uncomfortable for everyday wear. By the late 1960s, a growing environmental consciousness emerged, and the idea of throwaway garments seemed wasteful and unnecessary (Cunningham & Lab 1991; Jackson, 2021).

2.3.2 Textile Quality And The Role Of Durability

Quality is a multifaceted concept that can vary across situations, products, individuals, and locations. It pertains to how well a product is crafted, its materials, durability, longevity, and suitability for intended use. Quality may encompass various performance characteristics, including durability, appearance retention, ease of cleaning, and specific attributes like water repellence and flame retardancy (Taylor, 1993). High-quality products are often associated with higher retail values or luxury markets.

In the early 1900s, luxury fashion houses and couturiers were renowned for their craftsmanship, fine materials, and meticulous attention to detail. While such brands continue to draw esteem for these principles, the luxury industry has evolved to accommodate the fast fashion paradigm in recent decades (Mahrukh, 2020).

Couturiers' early practices aligned with today's concept of a slow fashion economy, emphasising small, seasonal collections of high-value garments characterised by design, originality, and exquisite fabrics. These garments were often tailor-made and crafted by highly skilled, well-compensated labour (Mahrukh, 2020). However, the dominance of fast fashion gradually eroded luxury brands' market share. Many luxury houses adopted fast fashion elements, such as high-street collaborations, expanded seasonal collections, and ready-to-wear lines (Choufan, 2020). The COVID-19 pandemic further impacted luxury fashion sales and led to the cancellation of global fashion weeks, prompting labels to embrace digital marketing approaches resembling fast fashion's real-time outreach capabilities (Choufan, 2020).

The challenge with this acceleration of luxury fashion is not simply moving away from quality craftsmanship and highly paid labour towards outsourcing more cheaply made garments, but the association of the luxury label to a quality that no longer exists. An examination of high-end retailer Net-A-Porter's A/W 2022 product range reveals that certain high-priced, designer garments are not necessarily timeless pieces intended for long-term use but rather high-fashion, trend-led outfits that may be worn once or twice, akin to fast fashion party dresses.

For instance, Rick Owens' Dress 1, made of 91% cotton with an elastomultiester (elasticated polyester) blend and rubber coating, is challenging, if not impossible, to recycle at the end of its life. Dresses 2, 3 and 4, constructed from poly-blends featuring synthetic fibres like polyurethane, elastane, and acrylic, require specialised dry cleaning. Despite their high price tags and

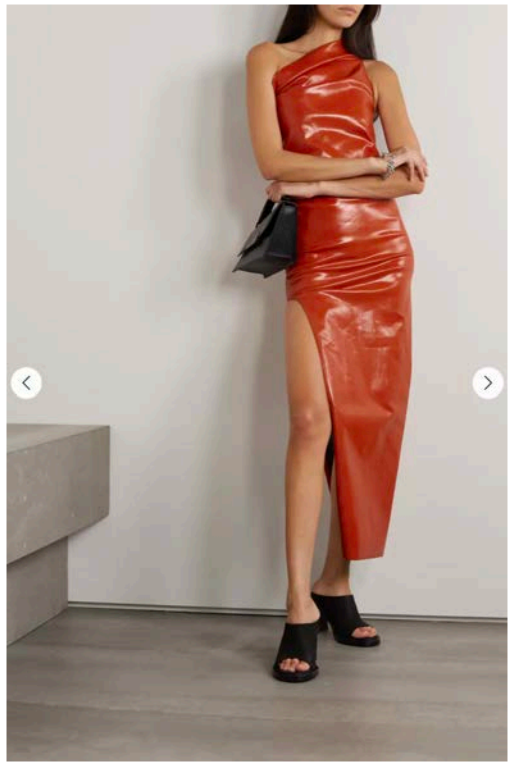


Figure 18: Coated Denim dress, Rick Owens, 2022.

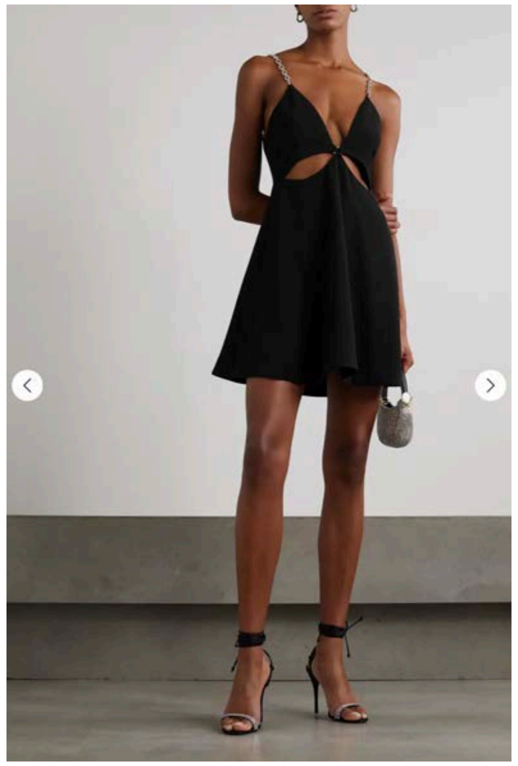


Figure 19: Embellished crepe mini dress, Jonathan Simkhai, 2022.

Dress 1: Rick OWens

- Athena one-shoulder coated demin gown
- £770
- Orange-Coated Denim
- 91% Cotton, 6% Elastomultiester, 3% Rubber
- Specialist Clean

Dress 2: Jonathan Simkhai

- Ellis cutout embellished crepe mini dress
- £500
- Black crepe
- 97% Polyester, 3% Polyurethane; Lining: 100% Polyester
- Dry Clean

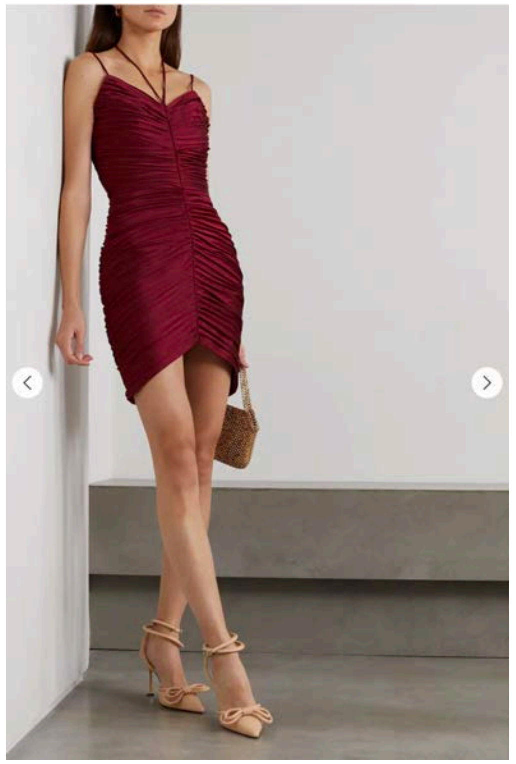


Figure 20: Satin mini dress, Rasario, 2022.

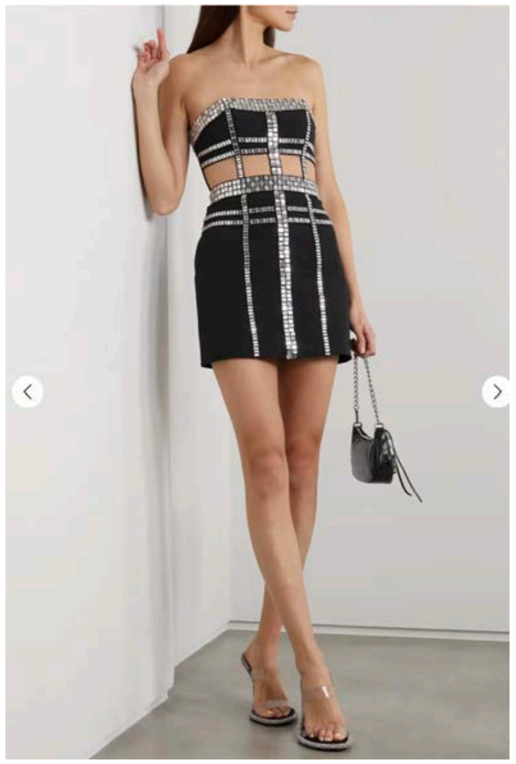


Figure 21: Crepe & mesh mini dress, David Koma, 2022.

Dress 3: Rosario

- Ruched satin Mini Dress
- £1,625
- Burgundy Satin
- 97% Polyester, 3% Elastane; Lining: 98% Polyester, 2% Elastane
- Dry Clean

Dress 4: David Koma

- Strapless Embellished Crepe & Mesh Mini Dress
- £1,870
- Black crepe, being mesh
- 52% Acetate, 45% Viscose, 3% Elastane; Trim: 100% Acrylic; Lining: 96% Acetate, 4% LYCRA
- Dry Clean

designer labels, none of these garments are designed with longevity, sustainability, or circular economy principles in mind.

LABFRESH asserts that all current fashion is essentially disposable (LABFRESH, n.d.), raising questions about quality, disposability, and materiality. If a garment will inevitably be discarded at some point, whether after one year or a hundred, should it not still be designed with eventual disposal in mind? Conversely, if a garment is designed to last a lifetime but is disposed of after one or two years, is it not still, in practice, disposable?

Chapman argues that the increasing pace of consumption is driven by emotions, with consumers using products as "existential mirrors" (Chapman, 2015; Haines-Gadd, Chapman et al., 2018). Rather than focusing solely on physical durability, it is proposed that designers prioritise emotional durability through a Durable Design Nine Framework (DDNF), which integrates emotional value into product development (Haines-Gadd, Chapman et al., 2018). This framework aligns with existing circular design strategies by emphasising product longevity and highlighting emotional value.

However, it is essential to recognise that not all products should be designed to last indefinitely. An industry-wide circular system must accommodate various price points and include all consumer demographics. For instance, children's clothing quickly outgrows its usefulness and often ends up in landfills unless upcycled or donated (Hanson-Lowe, 2019).

Designer Shahar Asor introduced children's shoes with an "expiration date" by aligning product longevity with material durability. These shoes, made from a biodegradable composite material, dissolve in the washing machine based on children's growth patterns, addressing fit issues and material longevity (Material District, 2020).

Connor-Crabb, Miller et al. (2016) highlight that the longevity of a garment is influenced by a complex interplay between the objects themselves, cultural norms, and individual behaviour (Goldsworthy, 2017). Even if a product is physically durable or emotionally cherished, it may not be worn regularly, suggesting that consumers will continue to purchase new garments, undermining efforts to reduce impacts over time. The shift in cultural perspectives, starting with the move towards throwaway living, has created a disconnect between expecting physical durability and discarding clothing after just a few wears. What is needed now is a level of social honesty, where we understand how long we genuinely need products to last based on style, occasion, and purpose and create products from materials that align with these authentic needs.

2.3.3 Challenges And Opportunities

Focusing solely on a design for longevity framework poses several challenges, given the current patterns of consumption and product disposal. While extending a garment's life by nine months can reduce carbon, waste, and water footprints by 20-30% (WRAP, 2015), evidence suggests that a cultural shift must precede the transition to a slow fashion system designed for longevity (Stenton, Kapsali et al. 2021). Until consumers embrace socially responsible consumption habits and prioritise "better" choices for both themselves and the planet over constantly seeking "new" items, a system dedicated solely to slow fashion may not succeed (Stenton, Kapsali et al., 2021).

Advocating for using "anti-fading and anti-pilling technologies" to enhance garment longevity (WRAP, 2014) fails to consider the hidden environmental costs. Applying such finishes to improve durability entails using additional chemicals, water, and energy during manufacturing. Additional environmental impacts may arise during care and laundering, such as the need for dry cleaning (Goldsworthy, 2017) and the release of microfibers (Napper & Thompson, 2016). Furthermore, durable materials, particularly non-biodegradable ones like polyester, can take a minimum of 200 years to degrade and may leach contaminants into the ground (Banwell, Schuknecht et al., 2020; McQuillan, 2020).

Another challenge is that durable materials, like virgin or recycled polyester, are often used in fast fashion products with short lifespans. This results in a mismatch between the raw material's production time and the product's use phase (Goldsworthy, 2017). This challenges the assumption that natural fibres are used in slow, high-quality production systems, while synthetics are for low-quality, fast fashion (Stenton, Kapsali et al., 2021). Pre-assumptions that slow inherently equals better and that fast is intrinsically bad can be misleading, as inconsistent production methods can lead to an unbalanced product lifecycle.

The example of paper dresses, as discussed in section 2.2.1, illustrates this mismatched system. Initially, paper dresses may seem like a fast, environmentally friendly garment option due to their natural biodegradability and potential for recycling. However, paper production is slower than anticipated, considering the time needed to grow trees before harvesting. Trees typically mature at 25-40 years old, with thinning occurring at 12-15 years to promote new growth (Spicer, 2014). Additionally, many paper dresses were made from a blend of materials, including nylon and cellulose-based materials, and featured plastic-based coatings, blurring the line between fabric and paper, natural and synthetic (Auerbach George, Tregenza et al., 2023).

The fact that these dresses were designed to be worn once, or a handful of times at the very most, raises the question of why they were made with increasing durability. Visits to both the Metropolitan Museum and the Brooklyn Museum to view several paper dresses up close confirmed that on many garments, seams were still sewn and overlocked and finishes such as facings and bias bindings were used on necklines and armholes – often introducing a third or fourth material into the mix. Aside from material diversity, large, screen-printed designs and customisable stickers featured heavily on paper garments, adding additional environmental toxicity through chemical-based inks and adhesives (discussed in section 6.3.1).

Filipa K's "throwaway dress," developed in collaboration with the Mistra Future Fashion Project (Goldsworthy, Earley et al., 2019) is an example of a disposable garment aligned with material and product longevity. This dress was crafted from 100% biobased and biodegradable non-woven Tencel fabric dyed using food waste. The rationale behind this garment was to maintain fast fashion consumer behaviour without the negative consequences by allowing consumers to cherish a garment for a short time (Filipa K, 2019).

In the context of rubbish theory (Thompson, 2017), we can observe the transfer of value (or lack thereof) across different types of fashion. Whether fast or slow, clothing starts in a transient state and eventually becomes rubbish for the majority. Some exceptions, like haute couture or collectable items, transition to a durable state. Through the circular economy, an opportunity arises to transfer value from rubbish back to transient, often involving textile recycling, upcycling, or resale, necessitating new technologies (Hall, 2021).

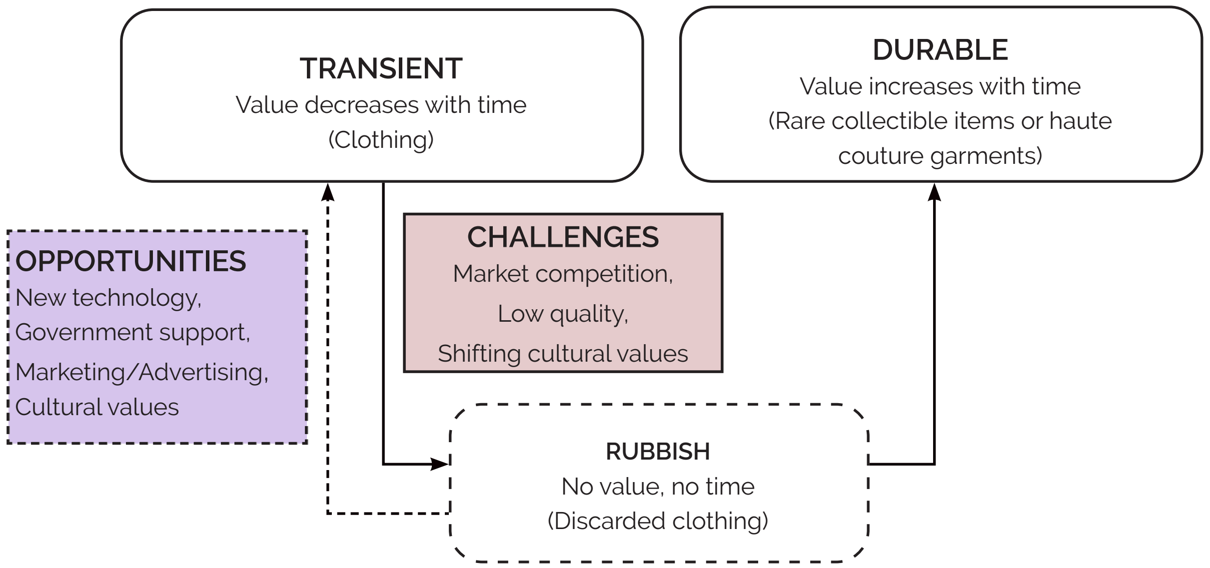


Figure 22: Creating a circular approach - Rubbish Theory hypothesis can be used to explore opportunities for turning rubbish back into transient items. Here, the opportunities have shifted from creating new products (as demonstrated in Figure 8) to creating products from waste (or rubbish).

Responding to Figure 22, the critical question is how to make clothing as suitable as possible for this transfer of value from rubbish back to transient. While not originally part of Thompson's framework (2017), this adaptation is essential for advancing toward a circular economy.

2.4 Transitioning To A Regenerative Economy

This section responds to objective three by investigating how switching to a more regenerative industrial system can aid and potentially begin to reverse some of the extreme environmental consequences caused by the textile industry discussed throughout the research so far. Existing regenerative initiatives in fashion, farming and agriculture discussed here have been explored and applied to the concept of an RDF using casein-based materials (Chapter 4).

In this section, the origins of regenerative agriculture have been explored before investigating how regenerative technologies and manufacturing methods are now being applied to the fashion and textile industries. A critical eye has been used to assess the data and decipher what can be taken forward to help build the methodological framework (Chapter 3).

2.4.1 The Origins Of Regenerative Agriculture

The term "regenerative agriculture" was first used in the 1980s by the Rodale Institute when Rodale Publishing established the Regenerative Agricultural Association (Rodale Institute 2020). While organic farming restricts GMO crops, synthetic pesticides, and fertilizers, regenerative farming goes further, aiming to reverse the effects of industrial farming through holistic farming and integrated livestock grazing practices. These techniques rebuild organic matter and restore biodiversity in the soil, leading to carbon drawdown and improved water cycles (Textile Exchange, 2022). Initially embraced by the food industry, these practices are gaining traction in the fashion and textile industry (FTI) (Senthil Kumar & Yaashikaa, 2018). Balogun (2022) emphasises that regenerative farming offers more benefits than just contributing to the 1.5° climate goal (Allen, Antwi-Agyei et al., 2019); it also aligns with a holistic approach to restoring ecosystems and achieving social equity.

Although these concepts may seem new, regenerative practices were initially employed by Native communities for centuries before settlers claimed the land and introduced the extractive agricultural methods we use today. While Indigenous Peoples currently comprise only 6.2% of the global population, they protect 80% of the remaining biodiversity (Textile Exchange, 2022). Supporting and learning from indigenous communities is crucial to achieving a regenerative economy and meeting emerging industry guidance regarding conscious design practices such as COP (United Nations 2022b), the Paris Agreement (United Nations, 2015) and the Convention on Biological Diversity (United Nations, 2022a).

Livestock farming for meat and dairy production carries a negative environmental reputation, including deforestation, overuse of antibiotics, poor waste management, and greenhouse gas emissions. In the 1960s, Allan Savory introduced "holistic grazing" as a method to combat desertification, now an integral part of regenerative farming (Ellen Macarthur Foundation, 2019).

Holistic grazing, within holistic management, is a flexible approach based on rotational grazing and local resource use. However, its adaptability makes it challenging to test consistently across diverse grassland ecosystems (Nordborg & Röös, 2016).

In his TED talk "How to fight desertification and reverse climate change" (2013), Savory claims that holistic grazing can reduce atmospheric carbon dioxide levels to pre-industrial levels in decades and that grass-fed livestock are crucial for low-emission, sustainable food systems. These claims have received both praise and criticism from the scientific community. The "Grazed and Confused" report (Garnett, Godde et al., 2017) highlights that while managed grazing sequesters carbon in the soil, the overall offset is outweighed by greenhouse gas emissions from livestock rearing.

In the UK, a growing debate centres on farming methods and land use. Professor Ian Boyd suggests rewilding and transforming half of the nation's farmlands (currently covering 70% of the UK) into woodlands, occupying only 13% of the land (Carrington, 2017). This idea aligns with the belief that reducing meat and dairy consumption is crucial to addressing the climate crisis (Dimbleby, 2021). Conversely, the National Farmers Union (NFU) argues against reducing livestock to combat greenhouse gas emissions. Instead, the NFU proposes growing fuel for power stations, capturing and burying carbon dioxide to offset three-quarters of the UK's agricultural emissions (Carrington, 2019).

2.4.2 Materials And Compostability

Composting and biodegradability are pivotal to regenerative material development and sustainable waste disposal. Composting primarily involves decomposing organic materials, including food scraps and yard waste, into nutrient-rich soil conditioners through a controlled biological process (Innocenti 2003). In contrast, biodegradability is a broader term encompassing the ability of materials to break down into simpler substances over time naturally. While composting is a specific form of biodegradation tailored to organic matter, biodegradability applies to a broader spectrum of materials (Innocenti 2003).

Distinguishing between industrial and domestic composting is essential for comprehending the requirements of each process. Industrial composting facilities have the capacity and conditions necessary for accelerating the decomposition of various materials, including compostable plastics and textiles. To expedite decomposition, these facilities maintain controlled environments with optimised temperature, moisture, and aeration levels. Conversely, domestic composting operates under less controlled conditions. Home composters may not achieve the same decomposition rates as industrial facilities due to variations in temperature, microbial activity, and composting practices. As a result, materials certified for industrial composting may not biodegrade as rapidly or efficiently in domestic compost bins.

Certification processes are pivotal in distinguishing compostable materials and garments from conventional plastics. Various organisations and standards, such as ASTM D6400 (USA) and EN

13432 (EU) govern the certification of compostable products. These certifications validate a material's ability to break down into non-toxic components within a specified timeframe and under specific conditions, often aligning with industrial composting requirements.

Legislative and governmental support is required to facilitate the transition towards regenerative fashion and textiles on a commercial scale. Brands require external incentives and regulatory frameworks to restructure their business models and production systems, as emphasised by McQuillan (2020). Equally, consumers need accessible infrastructure and responsible disposal options to foster sustainable consumption habits.

Currently, the UK lacks comprehensive collection schemes for compostable materials. While some local councils offer garden waste collection services, textile and other forms of material waste still need to be addressed. Government initiatives such as the 2021 plan to enhance household recycling and food waste collection schemes focus primarily on plastics, with limited attention to compostable alternatives for textiles and materials (Defra, 2021; Net Zero Strategy: Build Back Greener., 2021). Although admirable, there is little mention of textile waste and any plans to encourage compostable, bio alternatives for materials are centred around plastics and packaging (Standards for bio-based, biodegradable, and compostable plastics Summary of responses to the call for evidence and Government Response., 2021). Implementing suitable legislation and policies encompassing regenerative materials is vital for ensuring the seamless integration of sustainable practices into the broader textile and fashion industry.

2.4.3 Emerging Regenerative Practices

The fashion industry is experiencing a noteworthy shift towards regenerative practices, marked by a growing interest in bio-based synthetic textiles and regenerative natural fibres. Earlier this year, Vogue proposed a switch from sustainable to regenerative practices in the fashion industry as a necessary move (Chan, 2022) and has previously published several other articles about the importance of supporting biodiversity (Chan, 2021a) and regenerative agriculture (Cernansky, 2021; Farrah, 2020) in the fashion industry.

Cotton constitutes a substantial portion of fibres used in the fashion, textile, and apparel industry (FTI), amounting to one-third of the total (Voora, Larrea et al., 2020). However, traditional cotton farming practices have detrimental effects, including drought, soil degradation, habitat loss, and pesticide use, all which impact biodiversity (Chan, 2021a). Similarly, both viscose and leather production contributes to deforestation. Approximately 150 million trees are harvested annually for viscose production, while an additional 3 billion trees are felled for various industries' packaging requirements (Canopy, n.d.).

Livestock farming for leather also plays a substantial role in deforestation, with the leather industry responsible for 70% of deforestation in the Amazon rainforest. Moreover, livestock-related deforestation releases approximately 340 million tons of carbon into the atmosphere each year, contributing significantly to global emissions (WWF, n.d.).

Various fashion and textile initiatives and organisations have emerged to combat these issues and promote regenerative practices. Canopy, a non-profit organisation, collaborates with 750 brands to transform supply chains, emphasising biodiversity and forest protection. Textile Exchange, another non-profit, supports regenerative agriculture and offers a comprehensive analysis of the evolving regenerative textile landscape (Textile Exchange, 2022). Fashion for Good has launched the 'Untapped Agricultural Waste Project,' aiming to develop technologies that convert agricultural waste into textile fibres (Fashion for Good, 2022). The USA-based non-profit Fibreshed also focuses on building regional fibre systems that regenerate soil and protect the biosphere (Fibreshed, n.d.).

Luxury groups Kering and LVMH have also initiated their regenerative endeavours. Kering established the Fashion Pact and the Regenerative Fund for Nature, pledging to safeguard forests and biodiversity within their brands' supply chains (Kerring, n.d.; The Fashion Pact, n.d.). LVMH, in partnership with Central Saint Martins (CSM) at UAL, introduced Maison/0, a regenerative luxury alliance addressing environmental emergencies through creative education (Collet, 2022). The alliance showcased a textile collection utilising regenerative wool, cotton, mohair, silk, and nettle dyed with bacterial dyes, algae pigments, food waste, and natural tannins such as pomegranate waste.

Figure 23: Prototyping Regenerative Textile Design, a Maison/0 research project (Collet 2022).

Beyond materials, the fashion industry is exploring alternative sources for dyes and inks, moving away from traditional, chemical-based options. Synthetic dyes derived from crude oil have long been the standard, with detrimental effects on aquatic ecosystems and local environments. Although the global adoption of natural dyes may not be feasible, the emergence of bio-based colours aligns with regenerative principles (Collet, 2022).

The significance of colour in textiles has been underscored in recent endeavours, recognising that colour plays an integral role in holistic textile development. Utilising food waste as a source of colour aligns with the project's holistic approach and supports the bio-circular model, facilitating composting at the end of a product's life cycle. Furthermore, the accessibility and safety of experimenting with food waste at home have made it a practical choice for colour development.

In addition to food waste-derived colour, bio-based synthetic textiles created from waste materials are gaining prominence. It is important to note that some of these materials, marketed as waste-derived, may still incorporate synthetic polymers such as polyurethane (PU) or Polylactic acid (PLA) (Stenton, Kapsali et al. 2021) potentially limiting their circularity. Examples of contemporary fibres derived from food waste include Orange Fibre, produced from citrus juice by-products and often blended with other fibres, and Pinatex, a non-woven textile made from waste pineapple leaves, serving as a natural alternative to leather (Ananas-Anam n.d.; Orangefiber, 2018).

The Agraloop Bio-Refinery, offered by the 'Waste to Fibre' platform Agaraloop, provides a comprehensive solution for agricultural waste streams and textile management. This innovative system transforms a range of food crop waste, including oilseed hemp, oilseed flax straw, pineapple leaves, banana trunks, and sugar cane bark, into high-value, scalable natural fibre products (Circular-systems: Agraloop, 2018).

2.4.4 Challenges And Opportunities

While numerous solutions are emerging to address issues in the FTI, it is essential to recognise potential risks associated with these initiatives (Stenton, Kapsali et al., 2021). As demand for bio-based and waste-derived materials surges, the prospect of harvesting first-generation crops for textile production becomes more prominent (Banwell, Schuknecht et al., 2020). H&M's involvement with bio-based materials is a prime example; despite using such materials in small eco-friendly ranges at present, H&M offers 12 to 16 fashion collections annually, with unsold apparel valued at $4.3 billion in 2018 (Sachs, 2019). As their 'eco' ranges gain popularity and expand, they also risk increasing wastage from unsold clothing. As the bioeconomy grows, fast fashion companies may also use less transparent suppliers to source their raw materials. Depending on the initial source of agricultural or industrial waste, the risk of depleting such raw materials becomes a threat, potentially diverting companies' interest toward first-generation bio-based fibres (Stenton, Houghton et al., 2021).

End-of-life aspects, including biodegradability and compostability, also pose concerns within bio-based solutions (Lee, Congdon et al., 2020). Since many of these emerging materials are still in their infancy, limited information is available regarding their disposal impact and potential environmental consequences if production scales up to meet demand. Comprehensive lifecycle assessments (LCAs) are imperative for each new material to identify areas of concern for current production levels and anticipated future demand. Additionally, a common misconception is that all biopolymers are inherently biodegradable (Chen, 2021). In reality, they often require specific end-of-life processing methods to degrade within a reasonable timeframe and prevent chemical off-gassing into the environment. Furthermore, blending compostable, bio-based materials with traditional synthetics or chemically treated natural materials may complicate disposal, necessitating energy and resource-intensive separation processes (ŠAJN, 2019).

The ethical dimension of utilising waste materials from the livestock industry is a prominent concern. For example, casein, a by-product of the dairy industry, relies on the industry's continued existence for its production. This raises questions about the suitability of raw material sources, considering waste alone as a sufficient criterion. This research contends that waste material sources should be held accountable for their business and agricultural practices, emphasising transparency to waste proprietors. As McQuillan (2020) suggested, establishing small-scale, local regenerative systems can address such challenges. Moreover, the development of transferable material systems, exemplified by Agraloop, offers flexibility and the ability to switch raw materials based on local availability and necessity, reducing dependency on a single waste source.

While casein serves as the primary example in this thesis, other RPFs can originate from various sources, including nuts, soybeans, and corn (Brooks, 2009). These materials are well-suited for a transferable system. In reimagining the cycle of rubbish theory, the value of food waste can be transferred to a transient state by developing new textile fibres, aided by new technologies, government support, marketing efforts, and shifting cultural values. Composting at the end of life also plays a role in this transition.

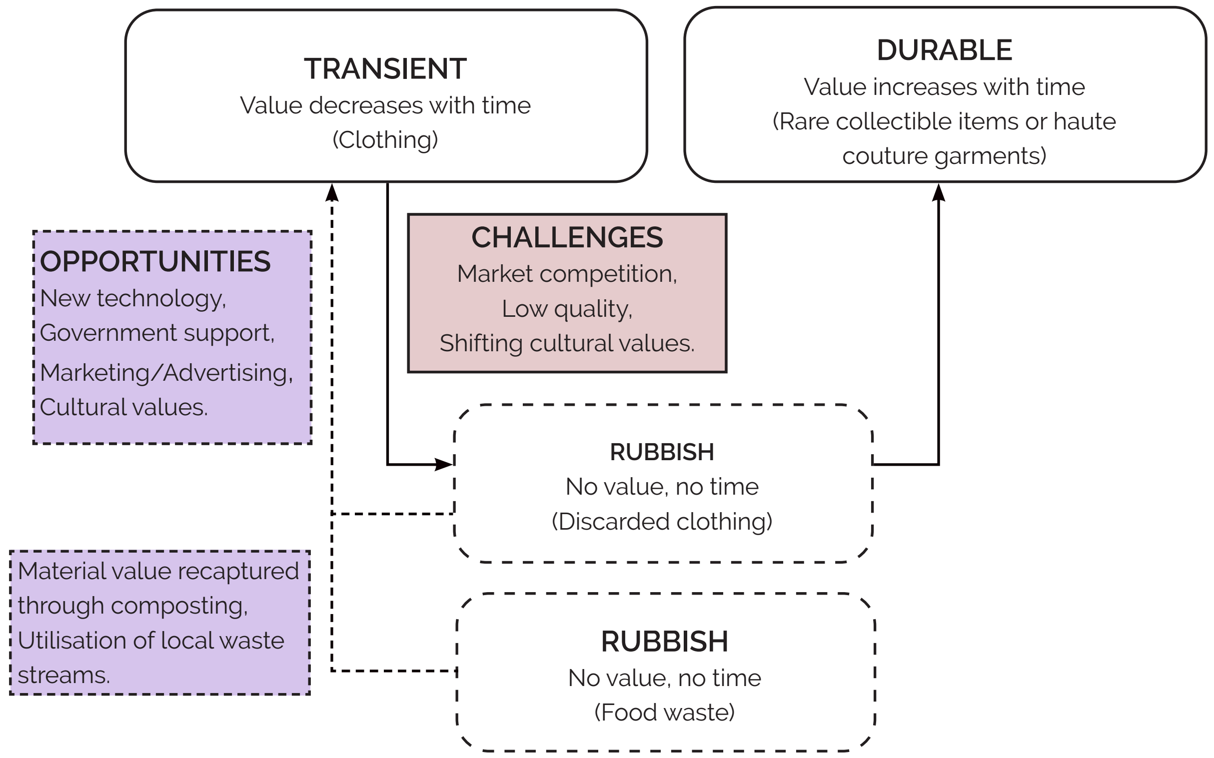


Figure 24: Responding to challenges and opportunities - Rubbish Theory hypothesis exemplifying the transition of RPFs through a circular approach from food waste to textile fibre, to discarded garment. (Thompson, 2017).

Towards The Fourth Generation of RPFs

Expanding on Brooks' original concept of generational RPFs, a fourth generation has been identified, covering RPFs created from the year 2000 onwards. This generation reflects responses to excessive consumption amidst economic challenges, coinciding with significant events such as the launch of the first online fashion retailer, ASOS, in 2000 and the Paris Climate Agreement in 2016, highlighting the tension between environmental concerns and consumerism. Within this fourth generation, Qmilk has made progress in developing and commercialising an eco-friendly casein fibre (2.2.2). However, substantial room for improvement remains in refining the systems within which these materials operate.

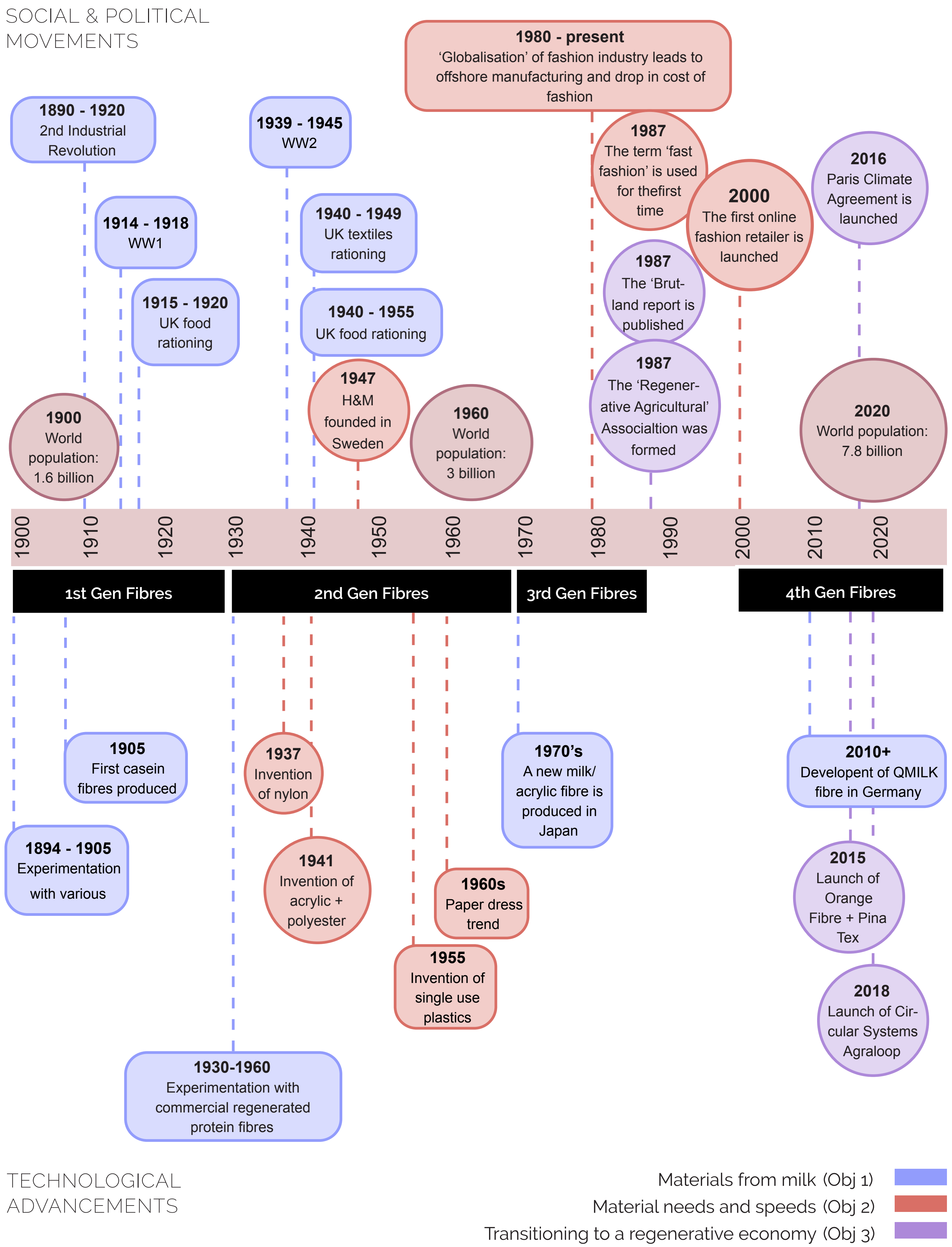


Figure 25: This figure expands upon Figure 9 (p26), representing an additional fourth generation of RPF in line with the development of new regenerative fibre initiatives.

2.5 Gaps In Knowledge

This comprehensive contextual review was crucial in delineating the methodology and scope of the practice-based research by identifying knowledge gaps. Employing a historically informed approach to address contemporary issues like waste and overconsumption, this research has unravelled a web of interconnected problems at their roots, yielding unique insights into each area of intervention.

The main knowledge gaps identified through this literature review are as follows:

1. **Technological Data on Early RPFs:** A noticeable gap exists concerning the technological data related to early RPFs. Information about their complete environmental impact across the supply chain, from raw material extraction to disposal, is scarce. Since sustainability was not a focal point until the release of the Brundtland report in 1987 (Brundtland, 1987; Niinimäki, 2011), essential details such as energy consumption, water usage, and disposal impact were largely undocumented. Moreover, much of the documentation regarding the manufacturing of early RPFs was destroyed after WWII due to the perception of it as a 'failed experiment' (Brooks & Rose, 2006). This knowledge gap presents both a challenge and an opportunity. Research can draw from historical precedents set during the 1940s and 1950s while adopting a modern, sustainable approach, considering the entire supply chain, from waste generation to end-of-life considerations.

2. **Testing Mechanisms and Life Cycle Assessment (LCA) Reliability:** Currently, there is difficulty in ascertaining the authenticity and dependability of textile certification schemes and LCA methodologies. Tackling large-scale issues often leads to multiple contradictory opinions and underlying incentives that may influence specific methods or outcomes. It is imperative to critically evaluate these approaches, considering who stands to benefit from them and how.

3. **Regenerative Farming Conflicts:** Debates and conflicts persist regarding the optimal path forward for measuring material or product sustainability and farming and sourcing raw materials. Disputes regarding land use and livestock rearing take centre stage in discussions on regenerative farming. While some argue that livestock are essential to ecosystems, others contend that the environmental harm caused by livestock outweighs the benefits of regenerative farming. Reducing meat and dairy production seems inevitable, raising questions about the viability of animal-based products such as casein and whether they are ultimately a lost cause.

4. **Consumer-Based Information:** Consumer preconceptions regarding textile quality and disposability lack comprehensive data, particularly concerning specific garment expectations rather than general clothing use. For instance, while statistics reveal that, on average, clothing is discarded after only ten wears (Pulse of the Fashion Industry., 2017), there needs to be more information on the expected lifespan of individual items like t-shirts compared to jeans or dresses. Such insights would inform designers about durability targets for distinct clothing items.

Key Questions:

The key questions that have been identified as a result of these gaps in knowledge are:

- Is casein a suitable raw material to produce regenerative fashion?
- What will these new, regenerative systems look like and how will value be recaptured at end of life?
- What policy and instruments are key to implementing these systems?
- How do we ensure that the solutions put in place are in the genuine interest of all stakeholders? (Supporting people, planet, and profit).

Each of the highlighted gaps in knowledge along with the key questions, are considered throughout the practice-based investigation (Chapters 5 & 6) and are revisited in Chapter 7 for analysis. Here, it is reviewed whether (and if so, how) each point has been addressed or what opportunities there are for further investigation.

2.6 Summary

The area of biodegradable fibres from natural, renewable feedstock using regenerative methods is rapidly gaining traction. With fast fashion, a growing global population, and the increased concern over the sustainability and traceability of products, more impetus should be placed on finding and developing novel textile production and processing methods whilst reducing the excess waste created by our expanding population. Using casein from local sources of food industry waste as an example, we can shift away from our dependency on petrochemically derived fibres, creating localised systems without requiring additional land mass.

In the early 1900s, when casein was first commercially explored, physical durability was a genuine requirement of clothing which needed to last longer due to textile rationing and lack of available styles. However, we must now find suitable solutions for the quick turnover of trends and low-cost garments, emphasising the matching of speedcycles and genuine consumer needs. Although creating products from waste is not a new concept, switching to an alternative bio-based, regenerative system offers the opportunity to explore new garment models where the emphasis is on low-input manufacturing techniques and end-of-life solutions. Within this model, our understanding of textile quality is redefined, prioritising the recapturing of value.

As discussed by Remy et al. (Remy, Speelman et al. 2016) "innovation in the way clothing is made has not kept pace with the acceleration of how they are designed and marketed." Similarly, definitions and assumptions of quality have remained the same over time, whilst consumer needs have changed. Although casein as a raw material might offer a technical solution to some of these problems, we must reconsider our current behaviours surrounding our relationships with garments.

Section 2.2 illustrates that the perceived quality of casein-based textiles was critical to its lack of commercial success; garments made from casein were considered weak, difficult to care for and would often be cut up for rags after just a few uses. As evidenced in section 2.3, there is a clear preconception that slow equals better. Better, however, depends on circumstance and fitness for purpose. As discussed, the argument of fast Vs slow fashion lifecycles must consider the specific properties of a textile fibre beyond the cost of production and avoid the mismatch of slow materials with fast cycles (and vice versa). In the context of garment speedcycles, the expected duration of use by the consumer must first be understood by the designer when selecting and developing appropriate materials (Goldsworthy, 2017).

This research proposes a shift in the definition of quality away from material attributes and towards a reflection of genuine fitness for purpose and (considering that ALL products will be disposed of eventually) what value can be recaptured at the end of life. Thompson's Rubbish Theory has played an essential role in understanding the rise and fall of RPFs over time, along with the transient nature of garments in general. This shift in thinking allows us to regard what were once the downfalls (low strength and wet tensile strength) of casein textile fibres into positive attributes, considering the quick turnover of styles and natural biodegradability.

Arguments surrounding the rearing of livestock, along with a rising vegan population, still leave much to consider in terms of the development of fibres dependent on livestock, such as leather and casein (which is reliant on the dairy industry). There is still much debate surrounding land use and sustainable farming practices in the UK. Along with an increase in vegan alternatives for dairy products, there is reason to question whether casein is the best option for waste material. Ethical dilemmas such as this, however, demonstrate the importance of knowledge exchange and transdisciplinary relationships between designers, material developers, agriculturists, scientists, historians, sociologists, governments, policy writers, consumers, and indigenous communities to develop an entirely new fashion and textile discipline which revolves around respectful and regenerative practices.

3

METHODOLOGY

The methodology chapter introduces existing theoretical approaches to knowledge exchange and regenerative design. My role as a textile designer and my specific contribution to the project are discussed in context to the initial brief set by the BFTT, highlighting adaptations made over time. Three nested methodological approaches form a unique design framework: transdisciplinary practice encompasses transition design, with regenerative design at the framework's core, creating a 'Russian doll' approach to the methodology, as shown in Figure 26. Ten methods employed within the original design framework align with the research objectives for acquiring new knowledge.

Moving forward, a distinction will be made between general casein fibres and those explicitly produced in the lab for this project. Lab-produced fibres will be referred to as "filament," while "fibres" will describe commercially purchased casein fibres, those mentioned in the literature, and any future casein-based frameworks and systems.

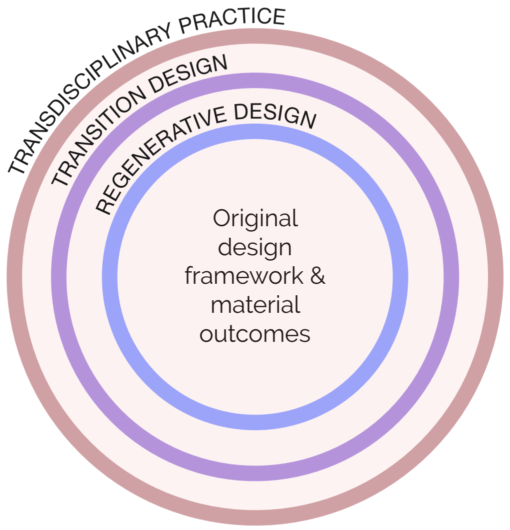


Figure 26: The nesting of methodological approaches

3.1. Transdisciplinary Knowledge Integration

This study employs a transdisciplinary approach to address the research question, aims and objectives, investigating the intricate connection between raw materials, fibres, and garments. The chosen methodology tackles complex environmental challenges within the fashion and textile supply chain, utilising casein to explore novel avenues for reducing waste, pollution, and toxic chemicals.

A transdisciplinary approach, combining science and design, is essential in achieving the research objectives. This approach offers a holistic understanding of the research question and subject matter. While design contributes valuable insights and creative problem-solving, integrating scientific knowledge adds depth and rigour through a systematic, evidence-based decision-making process.

This section introduces the transdisciplinary methodology and its impact on the research process and learning outcomes. The collaborative relationship between Dr Joseph Houghton (JH) from the University of Leeds (UoL), Hannah Auerbach George (HAG) from the Victoria & Albert Museum (V&A), and myself (MS) from the London College of Fashion (LCF) is also established. The theoretical transdisciplinary framework is outlined while considering the role of the textile designer and the integration of knowledge among researchers and disciplines.

3.1.1 Transdisciplinary Research

"An [integrated] approach is possible, but only if we can face theoretical possibilities that transcend our specialised disciplines. It is not enough to become multidisciplinary in the hope that an addition of all the disciplines will lead to a new vision. A major obstacle to the development of a new perspective lies in the very fact of specialisation itself" (Wolf, 1982: p.19).

As discussed in section 2.3 of this thesis, we face increasingly complex and dynamic societal and environmental issues known as "wicked problems" (Buchanan, 1992; Irwin, 2004; Irwin, 2012; Rittel & Webber, 1973). Any single discipline cannot tackle these wicked problems because they are not individual or contained; instead, they are 'intrinsically linked in a meta-system of problems' and, as such, cannot be solved in isolation (Mauser, Klepper et al., 2013; McPhee, Bliemel et al., 2018; Özbekhan, 1970: p.13; Rittel & Webber, 1973). Jantsch (1972) argues that these complex situations require a transdisciplinary approach. Transdisciplinarity is a scientific framework integrating knowledge from various disciplines and stakeholders to solve interrelated global conundrums (Lang, Wiek et al., 2012). It can be defined as "action-oriented" and "future-focused", "participatory", "holistic", "purposive" (Jantsch, 1972; Klein, 2002; Polk, 2015).

Key benefits of this type of research, which transcends disciplinary and interdisciplinary approaches, are the integration of knowledge from various scientific and societal bodies of knowledge and the production of knowledge beyond problem analysis. This type of collaborative effort between researchers and non-academic stakeholders can also increase "legitimacy, ownership, and accountability for the problem" and the solution options (Lang, Wiek et al., 2012: p.26). As such collaborative and multifaceted projects are gaining popularity in academia, terms such as 'multidisciplinary', 'interdisciplinary' and 'transdisciplinary' are often used interchangeably, without a clear understanding of each definition (Lawrence, Williams et al., 2022). Transdisciplinary innovation differs from multidisciplinary and interdisciplinary approaches in placing interactions within an integrated system, resulting in an evolving and adaptive practice (McPhee, Bliemel et al., 2018). This makes it possible to study multifaceted global-scale issues holistically, deploying myriad perspectives at multiple levels across spatial and temporal dimensions (Darian-Smith & McCarty, 2016).

To clarify the key differences, 'multidisciplinary' research involves researchers from several disciplines working independently and sharing information and results to combine findings at the end of the project. Interdisciplinary research involves a closer collaboration between disciplines, including transferring methods and knowledge, leading to the development of new fields (Jahn, Bergmann et al., 2012; Lawrence, Williams et al., 2022).

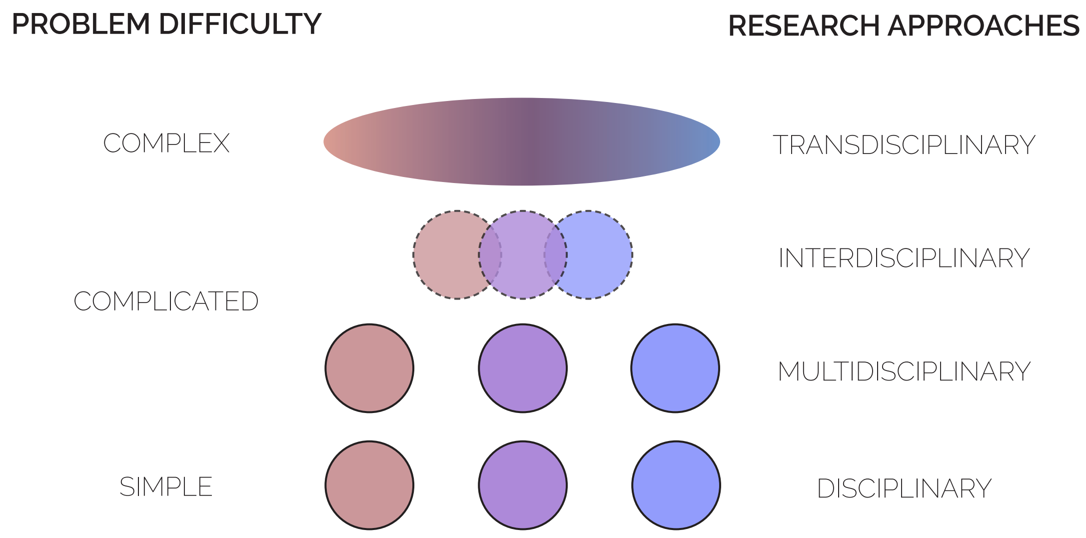


Figure 27: Transdisciplinarity (Darian-Smith & McCarty, 2016).

A widely used three-phase conceptual model of transdisciplinarity dissects transdisciplinary research into three main phases: problem identification, knowledge integration, and action. Transdisciplinary research is instigated by societally relevant problems leading to scientific research questions. The three phases (demonstrated in Table 1) help to merge two distinct pathways: developing approaches (e.g., policies and regulations) to resolve societal issues and developing interdisciplinary strategies and scientific insights applicable to the issue under review (Lawrence, Williams et al. 2022). Although this is indicated as three consecutive stages, phases can be moved between as freely as necessary, creating an iterative and recursive cycle (Lang, Wiek et al. 2012).

Phase	Transdisciplinary Research Process	Description
1	Problem Identification	"Collaboratively framing the problem and building a collaborative research team".
2	Knowledge Integration	"Co-producing solution-oriented and transferable knowledge through collaborative research".
3	Action	"(Re-)Integrating and applying the produced knowledge in both scientific and societal practice".

Table 1: The three stages of transdisciplinary research (Lang, Wiek et al. 2012, Lawrence, Williams et al. 2022).

Types Of Information

Learning is an inherent part of this framework, which is also necessary to keep up with an abundance of new and ever-changing information. According to Brown (2017), the best way to adapt is by creating 'knowledge flows' through participation and collaboration. Transdisciplinarity encourages new ways to address these complex issues by employing political, social, and economic agents and ordinary citizens (Clark, 2002) to move innovation beyond a "customer-centred" to a "society-centred" perspective (McPhee, Bliemel et al., 2018). In this sense, a holistic understanding of the environmental consequences of the decisions made within this research (not only within the design process) was fundamental. An exploration of the socio-political factors surrounding fashion and consumption was also required.

Lawrence, Williams et al. (2022) describe four critical types of information generated and applied through the transdisciplinary research process: Systems knowledge, orientation knowledge, transformation knowledge and process knowledge.

As demonstrated in Figure 28, the relationship between these four types of knowledge is

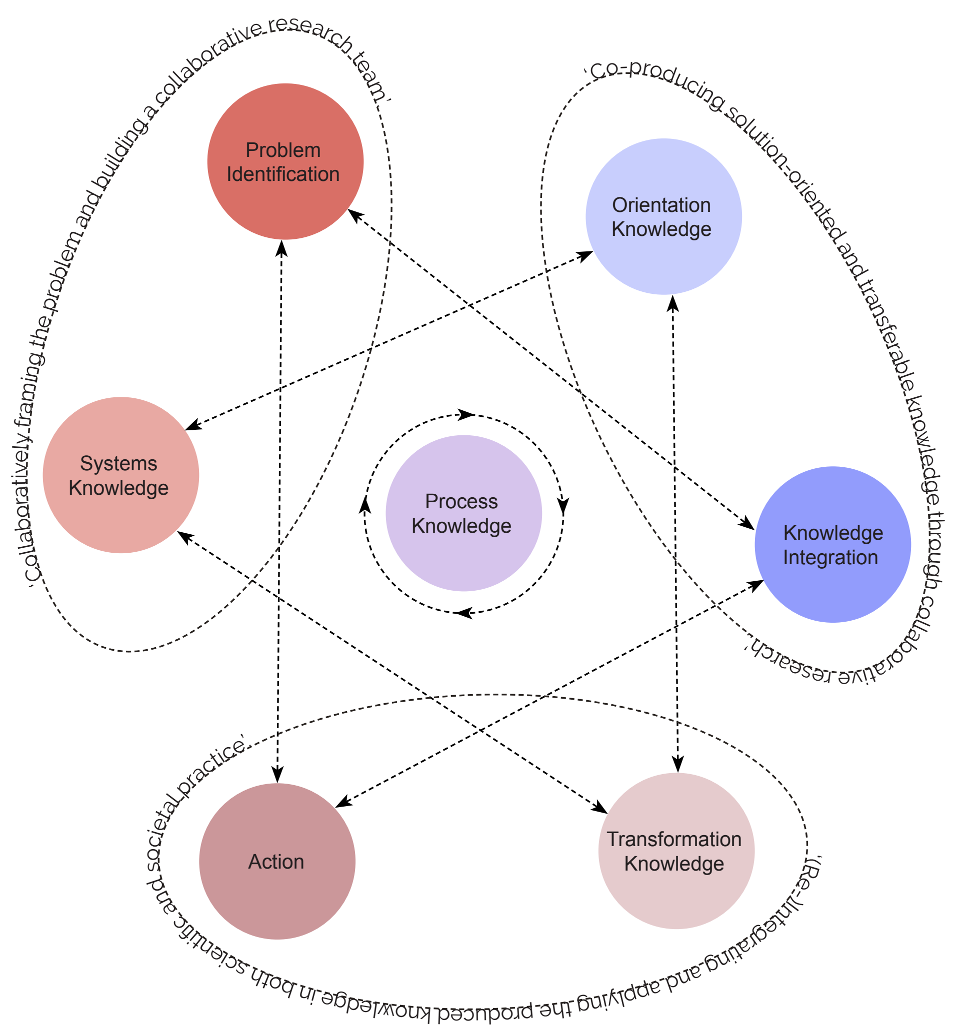


Figure 28: The relationship between each type of knowledge generated and applied in the transdisciplinary processes (Lawrence, Williams et al., 2022) mapped again the three phases of the transdisciplinary research process.

Type of Knowledge	Description
Systems knowledge	"Empirical and theoretical studies spanning the spectrum from the specific, disciplinary understanding of a single phenomenon to an integrative, interdisciplinary perspective on complex relationships between phenomena."
Orientation knowledge	"The formulation and justification of the goals and objectives of social change processes."
Transformation knowledge	"The understanding and/or development of practical (technical, legal, social, and cultural) means to reach the desired goals or objectives."
Process knowledge	"The methodologies and procedures needed to design and carry out TDR projects."

Table 2: Forms of transdisciplinary knowledge (Lawrence, Williams et al., 2022).

circular and cannot be organised in the same way as the transdisciplinary research phases indicated in Table 1. Process knowledge is central to integrating each of the other forms of knowledge and is essential to combine the activities of academic and non-academic actors during the three phases of the transdisciplinary research process as outlined in Table 2 (Lawrence, Williams et al., 2022).

Disciplinary Integration

Irwin (2012) believes that the fundamental principles of design can be applied from within every discipline, making collaborative, transdisciplinary design a crucial skill. Wahl, Orr et al. (2016) argue that transdisciplinarity is essential to whole systems thinking as it integrates relationships and perspectives into a 'dynamic understanding of the structures and processes that drive how the system behaves (Wahl, Orr et al., 2016).

Figure 29 demonstrates the transdisciplinary approach between researchers on the project from a fashion, textiles, scientific and historical perspective. Knowledge is exchanged concerning the original problem or question. As overlaps in interests and common ground are found (systems knowledge), the varied disciplines are condensed and moulded to form a new integrated framework (process knowledge). The historical context also underpins the cultural context, encompassing the fashion, textile, and science disciplines. Historical factors have informed all research areas and have been investigated by all three researchers in various forms. As demonstrated in Chapter 2, the historical investigation frames the cultural significance of RPFs, fast fashion and the rise of throw-away culture.

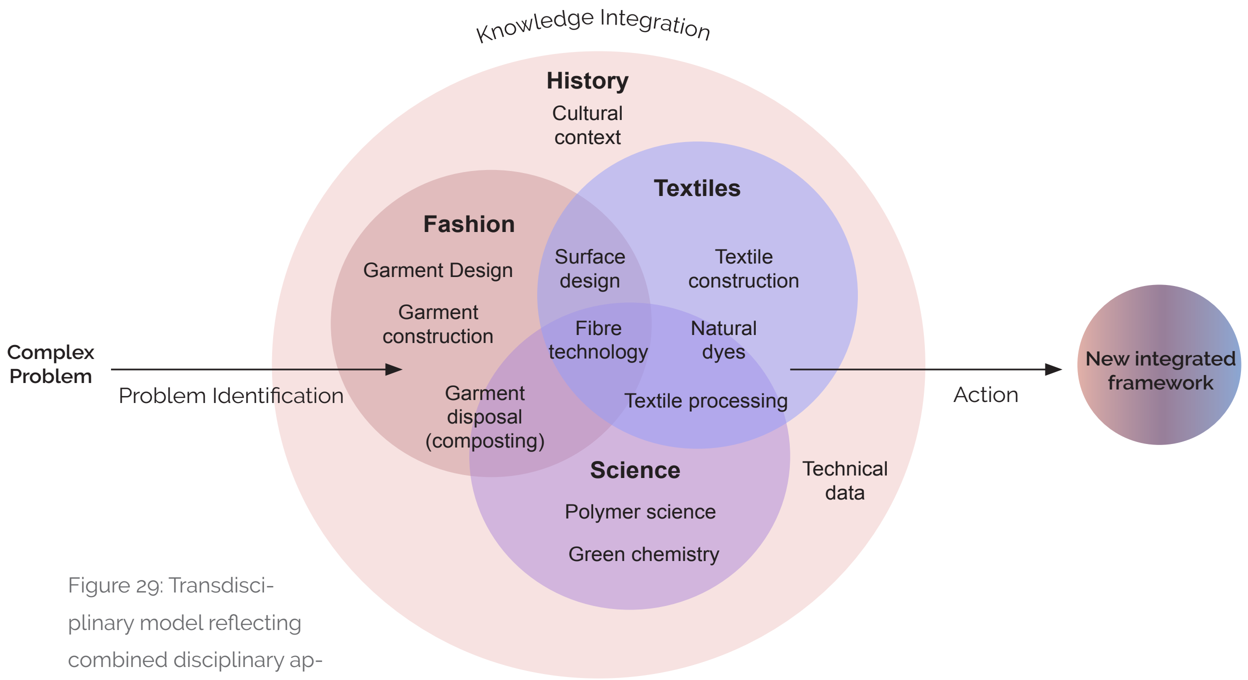


Figure 29: Transdisciplinary model reflecting combined disciplinary approaches taken within the three research phases.

3.1.2 The Role Of The Textile Designer

Practice-based design research is still a relatively new domain in academia compared to the scientific disciplines; as such, there is an ongoing debate surrounding suitable methods and approaches for generating new knowledge, (Vuletich, 2015). Igoe (2013) presents textile design as a sub-discipline within design, which has a unique thought process to other disciplines and is distinct yet inherently interdisciplinary. Regarding skill sets, Igoe proposes that textile designers have "formed a tacit understanding of a specific blend of design knowledge" (2013: p.30). These unique and often complex ways of thinking require distinct approaches to design and, therefore, have a different set of values (Valentine, Ballie et al., 2017).

The Textile Swatch

Textile designers are rarely involved in the chemistry of fibres and material processing, and instead, their primary influence is through decisions on organising fibres into textile structures (Kapsali & Hall 2022). Vuletich (2015) uses the textile swatch to explain the textile designer's role as 'to create a visual impression of a pattern or textile structure'. There are several disciplines involved in this process, from yarn spinning to textile construction (knit, weave, non-woven) and finishing (dyeing, calendaring, etc.) and post-production manipulation (printing, embroidery, etc.) (Kapsali & Hall 2022).

However, producing swatches can have limitations for textile designers, suggesting that their only skill is creating beauty and decoration. The processes or methods used hold little value or power (Vuletich, 2015). Igoe (2013) suggests this places the discipline in a secondary and anonymous role to other fields of design. Valentine, Baille et al., (2017) go as far as to state that the "textile designer is invisible" and that "the design process is often unarticulated" and ambiguous.

In her PhD research, Ellams (2016) argues that solutions for sustainability within the fashion and textile industry have split mainly into two independent disciplinary approaches, either scientific or design-based. Areas of priority are often identified as fibre choice, garment design and production processes, all of which science and technology have played a fundamental role in advancing sustainable alternatives and initiatives.

Without the designer, however, it is unlikely that such alternatives could reach commercial success due to a lack of aesthetic appeal and a disconnection from the consumer. Although it is becoming more common for designers and scientists to work together across areas of sustainable development, in the past, these roles have generally been carried out alongside each other rather than collaboratively.

Overcoming Challenges

As well as being an integral strength, one of the main challenges of transdisciplinary research is the combined engagement of academic and non-academic actors. It is a general concern that the involvement of non-academic actors, such as designers, may encourage the oversimplification of the research process and lead to superficial contributions or discussions instead of deeply engaged research (Lawrence, Williams et al., 2022). Lawrence, Williams et al. (2022) suggest that structured processes are required to emphasise the dynamic nature of cooperation between all actors involved.

In this research, the role of the textile designer (myself) was placed centre stage and valued with equal importance to that of the scientist (JH). Rather than limiting outputs to creating textile swatches using lab-produced casein filaments, I placed myself at the beginning of the transdisciplinary research process, allowing myself to contribute to all four types of knowledge as outlined in Section 3.1.1 (p59).

In terms of the material development process, this level of involvement allowed me to learn about the raw material and influence the fibres being produced in the lab early on. This experience also enabled me to recognise specific material properties and learn about the methods and processes being used in the lab, leading to a greater understanding of the potential challenges and opportunities in terms of sustainability and supply chain.

In this way, transdisciplinarity allows the textile designer and their work to be valued and play an equally important role as the material scientist. As we (textile designers) move away from solely providing beautiful fabrics to creating innovative and meaningful solutions, we can redefine our purpose and no longer be constrained or defined by 'the swatch'. By integrating the three phases of transdisciplinary research and proving a reflexive structure for creating new knowledge, each participating actor/researcher can make meaningful contributions and be valued in their own right.

3.1.3 Exchanging Knowledge And The Co-Creation Of New Knowledge

Transdisciplinarity work depends on integrating disciplinary creativity and should share a conceptual framework, drawing upon specific disciplinary approaches to address a common problem (Shiu, Tan et al., 2014). A study by Rhoten, O'Connor et al. (2009) discusses recommended guidelines for working collaboratively across disciplines and highlights the importance of creativity within the sciences. Creativity in science is necessary to combine diverse ideas, methods, and materials to produce novel questions or solutions. Interdisciplinarity is also widely considered one of the primary sources of scientific creativity (Shiu, Tan et al., 2014). Much like textile design, this idea presents science as a multifaceted approach to problem-solving and suggests that combining methods and findings from each discipline can produce new ideas and outcomes whilst framing the two industries as ideal collaborators.

In practice, transdisciplinarity and the co-creation of knowledge require a high level of collaboration between all involved, reaching beyond knowledge exchange and generating new ideas and actions (Fletcher & Tham, 2019; Wood, 2010). This process entails serious attention to the quality of relationships and team consciousness (Fletcher & Tham, 2019; Wood, 2010).

The co-creation of knowledge is a cyclical technique that begins with identifying a challenge (or wicked problem) and ends with the dissemination of the results of the research. This approach ensures that the investigation is relevant to the needs of society and that the results are accessible to a wide range of stakeholders (Mauser, Klepper et al., 2013; Shiu, Tan et al., 2014; Wood, 2010). Joint problem framing is essential to the co-creation of knowledge. This process brings together different perspectives to create a shared understanding of a problem by accessing tacit knowledge (Leonard & Sensiper, 1998). When done effectively, joint problem framing can help identify a problem's root causes, generate creative solutions, and build consensus on a course of action (Pearce & Ejderyan, 2020).

Mauser, Klepper et al. (2013) propose that the co-creation of knowledge is a three-step process involving academic and non-academic stakeholders. Like the three phases of transdisciplinary research, the first step is co-design, where stakeholders and academics work together to define the research goals and identify the relevant disciplines. The second step is co-production, where participating scientists and stakeholders conduct integrated research as a continuous exchange. The third step is co-dissemination, where the research results are published in accessible language and translated into understandable and usable information for different stakeholders. Mirroring the transdisciplinary research process, this is a reiterative and cyclical approach where stages are revisited based on the research need.

Phase	Transdisciplinary research process	Co-creation of new knowledge
1	Problem Identification	Co-Design
2	Knowledge Integration	Co-Production
3	Action	Co-Dissemination

Table 3: The three stages of transdisciplinary research mapped against the co-creation of new knowledge (Lang, Wiek et al., 2012; Lawrence, Williams et al., 2022; Mauser, Klepper et al., 2013).

Forming Transparent Relationships

Although ethnographic research on cross-disciplinary collaboration is rare, a study by Brodin and Avery (2020) outlines the difficulties of working between researchers in cross-disciplinary spatial and epistemic learning environments. Their research indicates that the quality of social interactions between participants largely determines the success of outcomes, suggesting that a common ground should be established from the outset. In another study, Delamont, Atkinson et al. (2000) found that forms of collaboration appeared most successful within sub-disciplinary areas where the individuals shared the same interests. The genuine sharing of interests will likely encourage transparent and open working relationships and inclusive communication across both epistemic spaces. It also allows participants to feel that their contributions are valued (Shiu, Tan et al., 2014).

Practitioners can ensure that transdisciplinary research processes are transparent by regularly reflecting on the process and outcomes with various academic and non-academic actors. Regular reflection helps reduce the misuse of knowledge and discrediting of science whilst building trust and credibility among stakeholders (Lawrence, Williams et al., 2022). By reflecting on the process and outcomes, transdisciplinary research practitioners can identify areas for improvement and ensure that the process is fair and equitable.

The relationship between researchers (MS, JH, and HAG) took face-to-face and online approaches. Face-to-face meetings were scheduled in the initial stages of research to discuss potential ideas, methods, and opportunities. As of March 2020, the UK entered a national lockdown, and all communication moved online. During this time, informal weekly meetings between researchers took place via Microsoft Teams to share updates, knowledge, and resources. These meetings helped assemble the project's first joint research paper (Stenton, Houghton et al., 2021). JH was then put on furlough, and communication and any other collaborative work halted until October 2020.

New ways of communicating online to facilitate the co-creation of new knowledge were developed by sharing research methods and results through project reports, written work, photography, presentations, and video and verbal communication. In light of Brodin and Avery's (2020) work, an open and transparent relationship facilitated a comfortable and trusting online presence where researchers could question, debate and discuss each other's work without fear of judgment. Transparency has been essential in establishing our individual roles and finding common ground to create new ideas. As a facilitating working environment was already in place when HAG joined the project in 2021, it also made it easier for her to establish her place within the team and contribute valuable knowledge immediately.

Figure 30 maps the transdisciplinary communication and knowledge exchange process as a timeline, considering project outputs within the three-step process of co-creating new knowledge (Mauser, Klepper et al., 2013). Key impacts to knowledge exchange, such as lockdowns, are plotted against project outputs and changes in creative direction. This visualisation of the project is essential to understanding specific challenges and opportunities faced throughout the PhD and how they were overcome or even utilised through transdisciplinary practice and the co-creation of new knowledge.

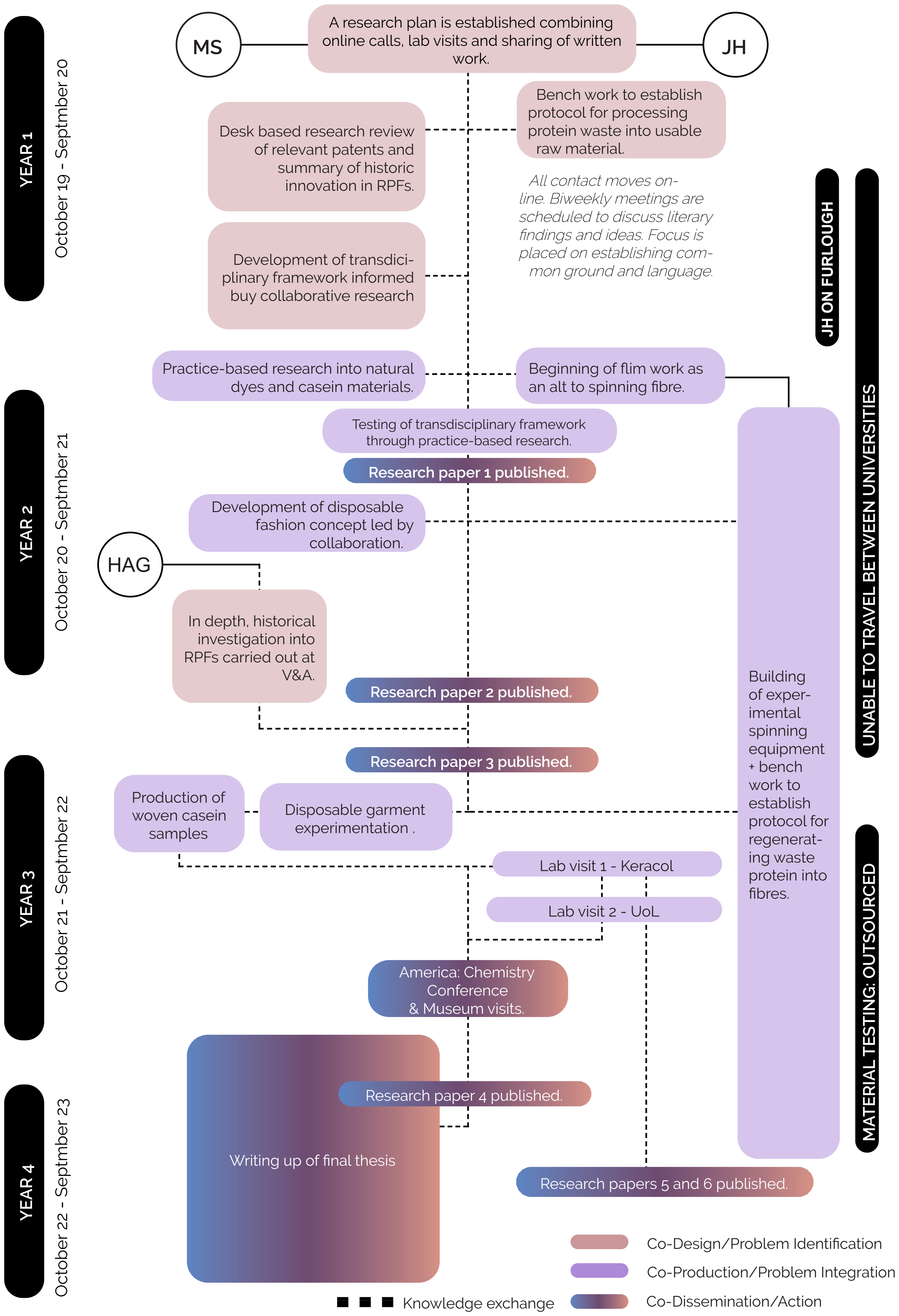


Figure 30: PhD timeline mapping knowledge exchange against the co-creation of new knowledge.

3.2 From Products To Systems

Transitioning away from the design of products and towards the creation of holistic design systems is an essential part of the RDF. By designing products in isolation, without considering the broader system of which that product would become a part, an opportunity to address the bigger picture is missed. In a systems-thinking approach to design, these systems can be nested within an earth-centric vision that accounts for all living beings.

In this section, two core design frameworks (transition design and regenerative design) are analysed and critiqued regarding their ability to create positive and lasting change. This lens is then applied to my own tacit knowledge of textile design and used to underpin the research whilst considering the broader societal context of implementing a systems-thinking approach to the FTI.

3.2.1 Transition Design

This research has taken a transition design approach (Irwin, 2015) to envision a future where disposable or transient fashion can (controversially) offer a solution to textile waste. This approach brings together an evolving body of practices (Irwin, 2019) that can be used to reimagine lifestyles and infrastructure surrounding disposable fashion within the concept of living system principles and regenerative design. Such methods also work harmoniously with planetary visions, such as the SDGs, in exploring how to bridge to a sustainable future (Iwabuchi, 2019).

Throughout each stage, transition design emphasises the need to engage all stakeholders (human and non-human) affected to create a shared problem definition and understanding (Irwin, 2019). These principles work harmoniously with the theories discussed by Brodin and Avery (2020) and, as mentioned in Section 2.3.2, are an essential part of the research to ensure that the genuine needs of stakeholders are met. In response to Objectives 3 and 4, engaging with stakeholders and creating a shared problem definition is essential to developing a transdisciplinary research and design process.

McQuillan (2020) suggests that to present a new vision for the future in the context of transition design, new ways of designing in response to a holistic way of seeing the world are needed. One suggested approach is simultaneous design, defined by Kathryn Townsend (2003) as a form of design practice which "merges textile and garment-led approaches by considering both the textile design and garment shape at the outset of the design process." Adopting this mindset and combining textile and fashion thinking was crucial for developing a sustainable approach to transient garments (documented in Chapter 6).

3.2.2 Regenerative Design

Regenerative design requires us to rethink how we design and construct our built environment to improve societal resilience, restore planetary health and regenerate ecological systems whilst ensuring a net positive impact. In the progression towards regenerative design systems for our planet, we must understand how to design for all species whilst respecting planetary boundaries and utilising science-based targets (Arup, 2020).

Regenerative design is systems-orientated and, as previously discussed (2.4.2), can include creating systems built to work harmoniously with nature, such as rewilding and regenerative agriculture. As a design framework, it has been primarily influenced by other ecological approaches, including biophilic design and biomimicry (Wahl, Orr et al., 2016). The principles of regenerative design are mainly implemented in areas of agriculture, architecture and city planning and (as with transition design) are concerned with transitioning towards a new economy and a future where people, communities, and ecosystems can thrive harmoniously (Hes, Stephan et al., 2018, Mang & Reed, 2012).

Implementing regenerative design techniques requires a living systems approach (1.1.3) to recognise the broader structures within which a product or service will operate. Mang and Reed (2012) refer to this as 'nesting'. For example, a garment is nested within a home, a home is nested within a community, and eventually, everything is nested within our planet. Recognising each of these levels as living systems enables a 'mutuality of interest' rather than segregating categories of the natural and man-made environment (Mang & Reed, 2012). Similarly, McQuillan (2020) proposes that methods of design should also operate within the wider worldview, nesting between the social foundation and ecological ceiling as defined by Kate Raworth (2017).

Figure 31 represents how garment design should be approached within an RDF. Rather than consider the garment a stand-alone item, it should be viewed as a connected and integrated part of a set of broader systems within our planet. This mode of thinking is also appropriate to transition design, which again urges the integration of design with community, social needs, and infrastructure. This ideology is complemented by the Regenerative Systems Thinking model, adapted from McQuillan's Zero Waste Systems Thinking model (2020: p.85). In this way, it is understood that the RDF outlined in this Chapter (3.4) is designed to work alongside a plurality of other frameworks and approaches which operate within this safe space and reflect a broader range of societal and environmental needs (McQuillan, 2020).

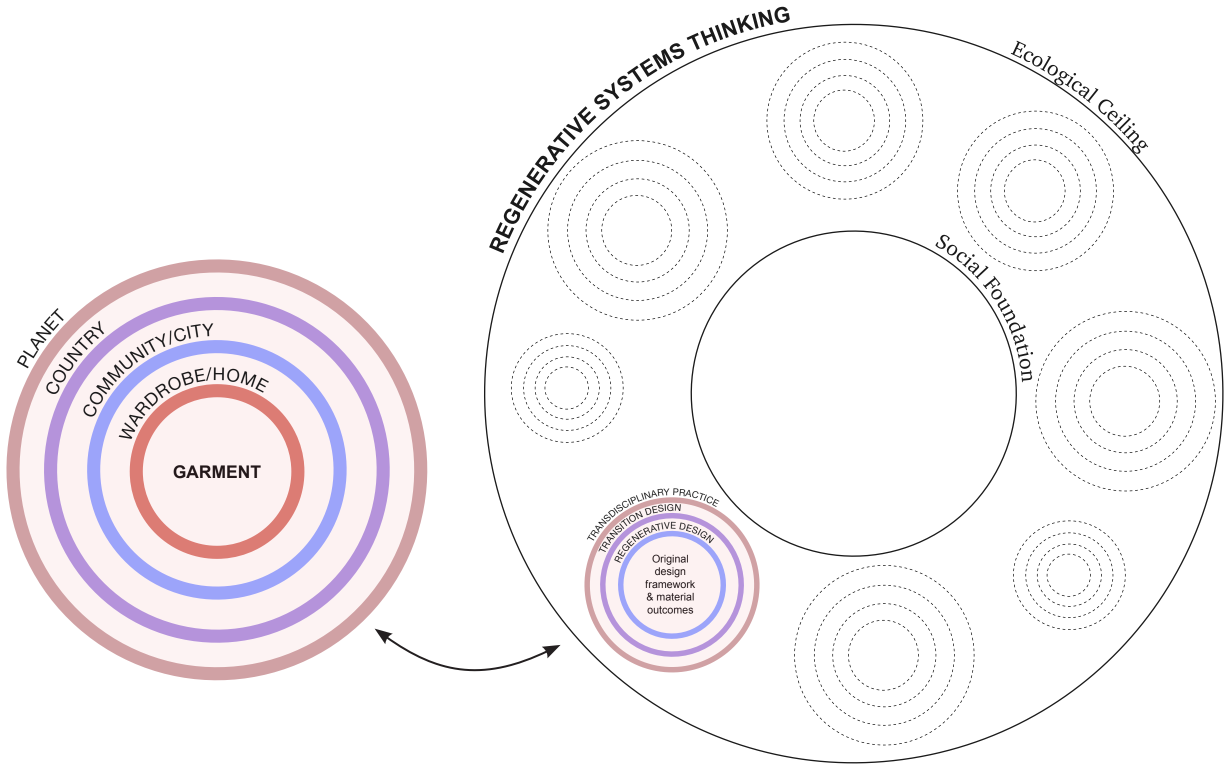


Figure 31: Transitioning from a garment design perspective to a Regenerative System Thinking perspective. Adapted from McQuillan's (2020) zero waste stystems thinking model.

When assessing existing frameworks for regenerative design (Brown 2018; Craft, Ding et al., 2017; Hes, Stephan et al. 2018; Lyle, 1994; Mang & Reed, 2012), comparisons have been drawn in terms of critical themes and stakeholders. Using the LENSES framework (Living Environments in Natural, Social and Economic Systems), which was designed to facilitate a large-scale regional development project in Victoria, Australia, as an example (Hes, Stephan et al., 2018) themes such as 'Land and water', 'ecosystems' and 'people and governance' have emerged through engagement with the land, its people, and its history. The same principles can be applied to fashion and textiles. Although garment design differs significantly from the design of built spaces, engagement with the land, communities and historical relevance in raw materials are essential influences for any regenerative design project.

As with the TED TEN (a collection of sustainable design strategies for textile and fashion designers) (Earley, Goldsworthy et al., 2016), the UN SDGs, and the 12 Principles of Green Chemistry (Anastas & Warner, 2000), there is much overlap in key themes with topics such as waste, land, water, energy, health and well-being, discussed across multiple frameworks. Identifying critical themes through the historical and contemporary investigation also helped identify stakeholders across multiple levels. Each stakeholder should be empowered to influence their field of action within the larger worldview, working towards a shared and agreed-upon vision of the future (Brown, 2018).

In her work with Maison 0 (Collet, 2022), Collet highlights important areas for intervention through a regenerative, circular design toolkit. Four key areas of the product lifecycle (material sourcing, manufacture, use and post-use) are used to guide design decisions and assess the broader impact of designs against biodiversity, climate, and communities. These three areas of impact are essential to the RDF. Rather than using them solely to identify negative consequences, they have been used as a criterion to ensure that final materials and garments have a higher positive impact whilst meeting all stakeholder needs.

The key themes and stakeholders identified within this research are demonstrated in Table 4 and mapped against these three impact areas. The mapping of critical themes and stakeholders against areas of impact further exemplifies the entangled nature and myriad potential issues when taking a holistic design approach. As demonstrated, each theme can be tied to all three areas of biodiversity, climate, and community in some way. The crossover between stakeholders also reflects the need for transdisciplinary collaboration not only between designers and scientists but also between farmers and agricultural specialists, manufacturers, government, consumers, and local councils.

The ambition to tackle a wide range of emerging themes, such as those demonstrated in Table 4, could be seen as unrealistic. However, setting a high bar can drive a higher level of innovation, allowing researchers to seek alternative solutions to fulfil the potential of the brief whilst leaving room for the outcome in question to evolve and be improved upon in the future (Hes, Stephan et al., 2018).

Theme	Impact/Opportunity	Stakeholders
Land	**Biodiversity/Climate:** Ensuring land is used and maintained in a way which provides natural habitats and encourages biodiversity and carbon capture.	Farmers, Designers, Government, Local councils
Soil quality	**Biodiversity/Communities:** Improving soil quality to encourage a wide variety of microorganisms such as bacteria, fungi, insects, and other organisms. Improving soil quality to promote the growth of crops & provide feed for livestock.	Farmers, Designers, Government, Local councils
Water	**Biodiversity/Communities:** Positive effects on aquatic life and habitats. Reducing water usage through the supply chain and product lifecycle and ensuring access to clean water for all.	Farmers, Manufacturers, Designers, Consumers, Government, Local councils
Energy	**Climate**: Using clean & low-energy processes to design and manufacture products and maintain products (e.g., through laundering).	Farmers, Manufacturers, Designers, Consumers, Government, Local councils
Ecosystems	**Biodiversity/Climate/Communities:** The creation of safe and nourishing ecosystems for all human and non-human stakeholders.	Farmers, Manufacturers, Government, Local councils
Waste (Food, water, energy, textile etc.)	**Biodiversity/Climate/Communities:** Reduction and recapture of waste through the creation of circular and regenerative systems. Reduction of waste sent to landfill. Access to household (textile) waste collection schemes.	Farmers, Consumers, Retailers, Government, Local councils
Well-being	**Biodiversity/Communities:** Mental and physical well-being for all stakeholders, including people and livestock, down to the smallest of microorganisms.	Farmers, Manufacturers, Retailers, Consumers, Government, Local councils
Equity	**Communities:** Can include forms of both social and economic equity, for example, fair wages for workers and affordability/ access to regenerative products suitable to varying income levels.	Farmers, Manufacturers, Designers, Retailers, Consumers, Government, Local councils

Table 4: Mapping of themes, opportunities, impacts and stakeholders.

3.2.3 Designing For Regenerative Speedcycles

Regarding speedcycles (Goldsworthy & Earley, 2017), working with regenerative systems across both fashion and agriculture could further assist in matching material lifespan to garment lifespan. Kapsali and Hall (2022: p.9) suggest using biology to "understand the impacts of resource efficiency, longevity and recovery through switching from a substance and energy approach towards designing with structure and information."

In this case, substance refers to fibres and materials, and energy refers to the effort and fuel required to collect and manufacture our materials. Our traditional manufacturing methods are very energy intensive, and today, energy in the form of fuel/food is scarce. Biology, however, could teach us how to better use our resources through an information-based approach to harnessing low-energy processes such as using microorganisms (Congdon, 2020; Kapsali & Hall 2022). In this way, information can be embedded into a structure (for example, within DNA) through biomimicry or biotechnology (Kapsali & Hall, 2022).

Kapsali and Hall (2022) refer to this as Design principles for resource efficiency, longevity, and recovery (RELR) (Table 5). Interestingly, longevity is referred to as lasting 'as long as required', meaning that a designated garment lifespan should be considered before material selection. In terms of taking a structure and information-based approach, longevity (or a designated lifespan) with enhanced resource recovery could be designed or programmed into a garment as a way of matching speedcycles.

Efficiency	Longevity	Recovery
Lean use of materials and energy	Lasts as long as required Lean repair/maintenance Has multiple functions	Lean release of energy and material at end of life

Table 5. Design principles for resource efficiency longevity and recovery (Kapsali & Hall, 2022).

One way of achieving this is through a mono-material approach. Mono-material approaches from a fashion industry perspective are uncommon due to several reasons. First, blended textiles can offer more properties and qualities than single-fibre textiles. For example, a poly-cotton blend can offer superior properties to cotton alone, such as crease resistance, durability, and breathability. Secondly, a fully mono-material garment requires all components, such as fastenings, to be constructed from the same material.

Goldsworthy (2012) explores mono-materiality as a solution to difficulties within textile recycling, claiming that single-material systems are preferable as there is no need to separate the product structure before processing. If mono-materiality were applied to natural materials (or certain types of biomaterials), biodegradability or compostability could be designed into the product from the outset. If we take this a step further and apply the principles of RELR to regenerative design, mono-materiality combined with a short yet designated lifespan could be designed into a product specifically for composting at end of life.

In her book about the shoddy industry, Shell (2020) describes the production of 'forced rhubarb' using leftover and unsuitable wool as a 'slow acting, nitrogen-rich fertiliser (Shell, 2020). As casein can be processed into a variety of materials (textile fibres, films, coatings, and bioplastics), not only does it serve as a starting point for a 100% mono-material archetype, but due to milk being rich in nitrogen, there is also potential for the nutrients provided from the raw material to be put back into the ground as a fertiliser. Referring to Table 4, there is scope here to address several key themes, including land, soil quality, energy, ecosystems, and waste.

Figure 32 demonstrates how each criterion discussed in this section (Key themes, Stakeholders, Supply chain and Areas of impact) can be grouped in various ways for investigation. By viewing each ring within the circle as a moving part that can be spun around, we can begin to comprehend the many ways that each area of impact can be addressed. Although it would be impossible to address all these areas at once, this wheel is a helpful tool for selecting and grouping criteria and considering the broader impact of a design throughout each stage of the supply chain.

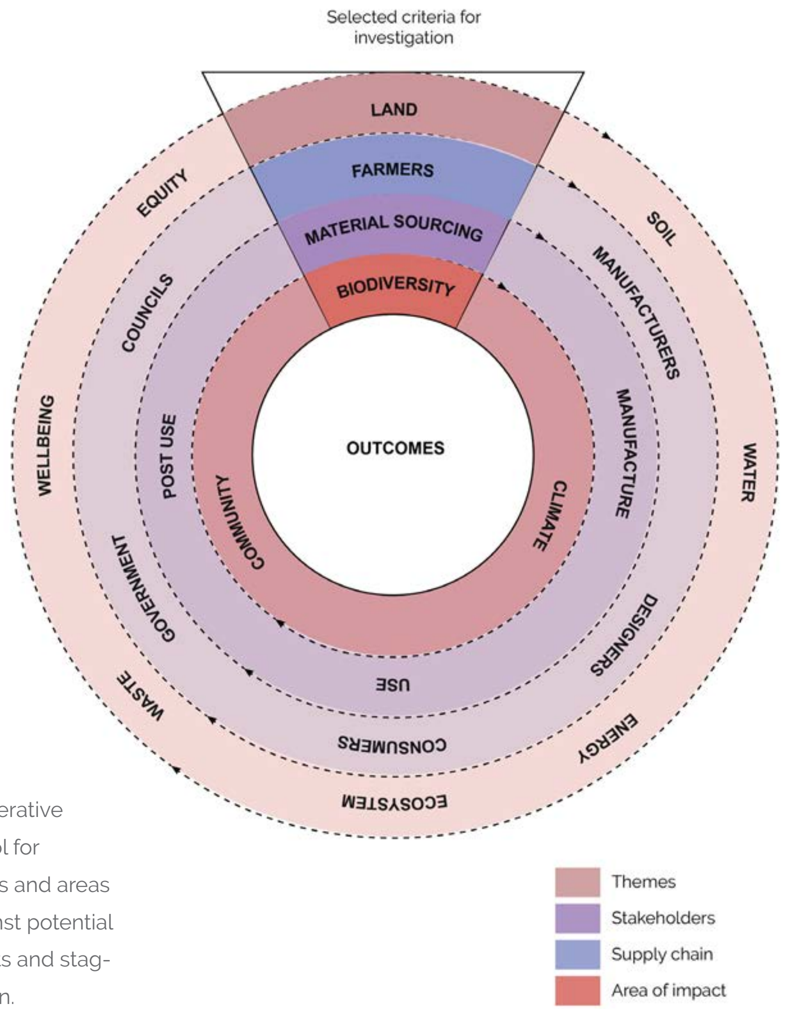


Figure 32: The regenerative design wheel is a tool for mapping key themes and areas of investigation against potential stakeholders, impacts and stages of the supply chain.

3.3 Combining Textile Practice With Chemistry

"The traditional divides that have existed between the disciplines of science and design are being dismantled with ever greater realisation of the importance of bringing in those who understand the product from the very beginning of development" (Kapsali, 2016: p15).

Alongside the biological and agricultural cycles discussed in this research, chemistry has played a significant part in the design process of casein-based materials and systems. Referring to the literature review (Chapter 2), the historical chemical-based process for developing RPFs, including casein, was reviewed and scrutinised from an environmental and social (health and safety, textile quality, etc.) perspective. The results of this investigation paved the way for developing a range of non-toxic casein-based materials to fit within an RDF, of which a tacit knowledge of textiles and materials was also essential.

This section draws upon designerly ways of knowing to demonstrate how textile practices combined with a newly acquired knowledge of chemistry-based processes have shaped the project and its outcomes. Scientific methods of thinking are also drawn upon, comparing and combining techniques from both practices to form new ways of designing.

3.3.1. Designerly Ways Of Knowing

Today, textile designers seek opportunities to design by facilitating change and using their design skills to develop alternative products, services and experiences (Valentine, Ballie et al., 2017). As such, there is an increased focus on ambitious and inventive co-design methods (Ballie, 2014; Vuletich, 2012), which are deemed necessary when driving the agenda for sustainability as a critical concern within the fashion industry. Valentine, Baille et al. (2017) believe that this requires a personal journey for textile designers to identify their values through the process of making, taking an imaginative and human-centred approach to innovation with design capabilities at the heart of the research.

Nigel Cross has significantly contributed to the discourse surrounding designerly ways of knowing (Cross, 2006). He argues that designers' "knowledge, skills, and values lie in the techniques of the artificial," which is gained through using and reflecting upon design activities and artefacts of the artificial world. This knowledge is inherent in manufacturing artefacts, which is achieved through making and reflecting (Cross, 2001). In this way, Igoe (2013) and Vuletich (2015: p. 53) consider how "knowledge is embodied in the textile designer's thinking and process and in the design outcome".

Both designers (Igoe, 2013; Vuletich, 2015) believe that textile design relies on tacit knowledge and experience, yet this can lead to a range of built-in rules which stem from years of practice and can block creative, free-flowing thinking. According to Collins (2001), there are three types of tacit knowledge: skills-motor, rules-regress, and forms of life. Skills-motor tacit knowledge is embodied knowledge that is guided by motor skills. Rules-regress tacit knowledge is knowing the implicit rules that should be followed in certain situations. Forms of life tacit knowledge begins with the acknowledgement that different people take on different information to be specific knowledge.

Tacit knowledge can be difficult to transfer as it is based on personal experience and perspective (Pearce & Ejderyan 2020). There are, however, potential solutions to such restraints. In her PhD work, Congdon explores how “bringing craft skill into unfamiliar territories can produce unexpected and innovative results” (Congdon, 2020: p.28). As a designer and maker, I have gained a comprehensive understanding of materials and processes by working with them first-hand. However, the transdisciplinarity of this project allowed me to pull that knowledge from a traditional (physical and conceptual) design space and place it in a new area. This is reflected not only in the laboratory-based work but also in the design work carried out in my own home during lockdown. My kitchen was transformed into a neutral space for designing and experimenting freely with casein-based materials. I was able to simultaneously wear the hat of the textile designer, the fashion designer and the scientist (Hall & Earley, 2019) and utilise my tacit knowledge without being hindered.

The designer is also likelier to work with traditional textile materials and processes in a conventional textile design space. For this project, however, there were many firsts in working with an unestablished raw material and learning how to process that material in various ways. As a designer and researcher, this allowed me to approach the design process with a fresh outlook. Although a lack of experience in some areas (weave and chemistry-based techniques) meant that time was needed to build the necessary skills, experience in other places (fashion design and manufacturing, print design and textile dyeing) was invaluable for assessing the quality and final outputs of the textiles produced, as well as creating a unique methodological approach.

3.3.2 Scientific Ways Of Thinking

In her work with tissue engineering, Congdon observes the requirement of tacit knowledge and skill in the laboratory through the execution of experiments (Congdon, 2020). Perhaps conversely to design, she notes that ‘this is still a process not represented in the literature surrounding science; the result is praised – not the technique that created it.’ Upon my own experiences of working in a lab (both at MA and PhD levels), I found that process and technique are still a crucial part of the knowledge exchange process and the final result. As with design, there is an iterative process to achieving a particular result, potentially leading to newly acquired tacit knowledge.

Much like designerly ways of knowing, the scientific process can also include performative methods, including (but not limited to) reconstruction, replication, and re-enactment of historical experiments and techniques (Henriksen, 2020). The repetition of historical techniques was a focal point for developing green casein-based fibres, as it was necessary to understand the

issues (both environmental and material) surrounding early patents for RPFs. This also demonstrates the importance of archival research in performative methods of scientific enquiry. Historians using performative methods emphasise the positive impact they can have on our understanding of the history of science, creating new opportunities to engage with historical subject matter and enriching existing methodologies (Henriksen, 2020).

When historical texts are difficult to disseminate or information is missing, a trial-and-error approach can be taken, allowing an approximate understanding of the tools, materials, conditions, and processes involved. Burkart believes that to learn something performative, e.g. cooking, knitting, or chemical experiments, texts alone are not sufficient and that practice (including failure), leading to tacit knowledge, is essential in developing both skill and understanding (Burkart, 2016). Again, this can be compared to traditional craft-based techniques such as embroidery, which have a rich history and offer a range of historical methods from which to learn.

In terms of the transdisciplinary methodology, a trial-and-error approach was used by all researchers involved. This approach was necessary for disseminating historical patents documenting the development of casein-based films and fibres in the laboratory, creating and using natural dyes and colouration methods tested at home, and constructing textile materials using techniques such as knit and weave in the studio. Although each area of development is different, requiring different skills and tools, these scientific ways of thinking and designerly ways of knowing were brought together through knowledge exchange to create a unique set of transferable, performative methods.

3.3.3 New Ways Of Designing

Although there is a rapidly growing number of methodologies for designing with science (Congdon 2020; Cross, 2001; Kapsali & Hall 2022; Ribul, 2021), it would be impossible to employ a single one for any project other than for which it was initially created. Any research project requires a tailor-made approach reflecting the necessary time, place, skills, knowledge, and tools required. Although a great deal of discourse surrounding ‘design science’ and ‘the science of design’ was created during the 1960s (Cross, 2001), most design methodologists agreed that designing itself could never be a scientific activity (Grant, 1979).

Rather than thinking specifically of design as a scientific activity or science as a design activity, this research investigates how both disciplines can inform each other through reflective practice (Schön, 1983) and knowledge exchange. Working directly with a green chemist (JH) and a professional textile weaver (HAG) allowed me to reflect upon my own tacit knowledge and understanding of design methods in a new way. Working directly with people with other skills and viewpoints helped shape the final research methodology and physical results of the research in an unpredictable way.

The practice-based approach of this research was necessary to learn new skills across the research team and to understand the properties and behaviours of casein-based materials in various forms. Working with casein-based materials across different physical spaces (laboratory, home, and studio) allowed a range of scientific, industrial and craft approaches for material development. In this way, materials developed in the lab affected the design of materials in the home and studio. Conversely, materials designed in the home and studio affected materials produced in the lab.

As discussed by Hall (2021: p.26) and Lerpiniere (2020: p.93), textile designers must bring together "disparate approaches, competencies and skills" to tackle the changes required in the industry, considering the entire lifecycle of a product (Lerpiniere, 2020: p.93) engaging with both the micro (fibre level) and the macro (supply chains) (Hall, 2021). In this context, a mono-material approach to textile design was positioned within the wider regenerative and transition design frameworks.

Figure 33 demonstrates how each approach is nested, becoming more focused as it reaches the centre. On the inside is mono-material design (micro) focused on innovation at a fibre or material level. This is encompassed by the regenerative design framework (macro), which is employed locally and concerned with local supply chains and stakeholders. On a broader system thinking level, transition design is used to deal with the broader context of the FTI on a global scale. For example, this could include government intervention or an incentive to abandon virgin raw materials altogether and move towards implementing regenerative systems on a global scale. Transdisciplinary practice sits on the very outside of the nest as it is necessary to approach each encompassing system from multiple disciplinary perspectives, leading to an altogether unique framework for designing garments.

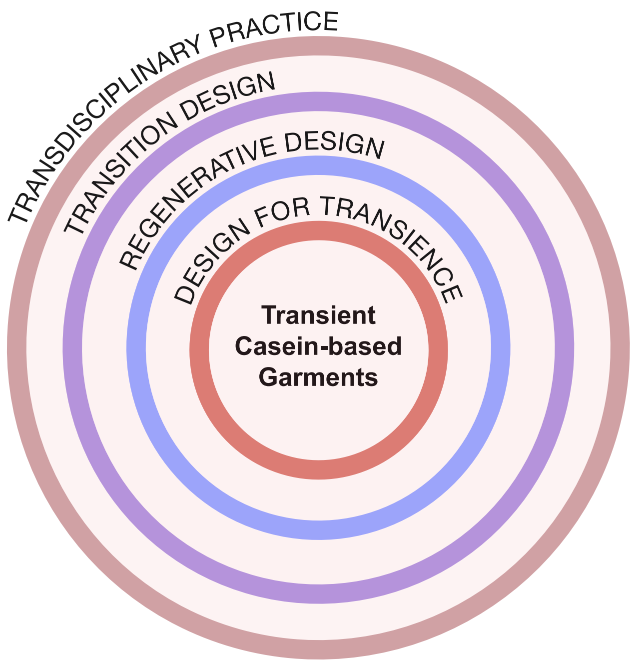


Figure 33: Taking a nested approach to garment design.

This research's design for transience element is reflected in the decision to develop mono-material garments from casein-based materials. Going forward, these will be referred to as transient, casein-based garments (TCGs). As discussed in Section 3.2.3, taking a mono-material approach can aid the recapturing of value at end of life as there is no need to separate fibres or other materials such as linings, facings, or components. Within the development of mono-material garments, alternative methods of joining fabrics that do not require stitching are also considered to avoid introducing a binding element such as sewing thread, which is usually a cotton polyester blend (Kapsali & Hall, 2022).

By once again removing the constraints of traditional methods of making, I was pushed out of my comfort zone and forced to explore alternative ways of construction which could also be suited to transient, mono-material garments. Such considerations included using zero-waste design and low-energy manufacturing methods (e.g., garments of a simple shape that are quick to put together and require minimal effort to make) (Kapsali & Hall, 2022).

3.3.4 Applying The Outcomes Of Knowledge Integration

Transdisciplinary research can be more rigorous and transparent if it includes regular reflection on the process and outcomes by various academic and non-academic actors (Lawrence, Williams et al., 2022). This reflection, known as reflective practice (Schön, 1983), has played a central part in this research and an essential role in applying the outcomes of knowledge integration.

Scrivener (2002: p.11) says, "If we are to give greater attention to the process of creative production, then this should focus on the recording and reporting of these moments of reflection, including intended and unintended consequences and responses to them". In this way, he claims that the systematic recording of making and reflection in action plays a crucial role in making the creative production process more accessible, both to the researcher and the research audience (Scrivener, 2002).

This collaborative methodology emerged from both the practice and theoretical elements of the research and is documented through the systematic recording of practice and interactions between researchers. Reflective practice through discussions, photography, note-taking, sketching and visual mapping was used to support the research process, illustrating interactions between researchers from the onset of collaboration and finding links into the broader fashion and textile system.

The outcomes of knowledge integration are reflected in the three key stages of the research methodology: Explore, Experiment and Evaluate. This structure reflects the three stages of the transdisciplinary research process (Lawrence, Williams et al., 2022) and the three stages of co-creating new knowledge (Mauser, Klepper et al., 2013). Within each of these stages is a range of research methods, which have been broken down and discussed in detail in Section 3.4. In stage 1 (explore), the outcomes of knowledge exchange are applied through the sharing of literature resources and the mapping of shared ideas to produce written outcomes in the form of research papers. In stage 2 (Experiment), knowledge exchange outcomes are applied through practice-based research and the sharing of results between the laboratory, the home, and the studio to produce material-based outcomes such as casein filaments, textile samples and garment toiles. In stage 3 (evaluate), knowledge exchange outcomes are applied to disseminating research through academic and non-academic stakeholders via consumer surveys, interviews, presentations, and material testing.

Phase	Transdisciplinary research process	Co-creation of new knowledge
Explore	Problem Identification	Co-Design
Experiment	Knowledge Integration	Co-Production
Evaluate	Action	Co-Dissemination

Table 6: Combining phases to create an original transdisciplinary methodology.

3.4 A Regenerative Design Framework For Transient, Casein-Based Garments.

This PhD project brings a creative enquiry into an often science-based discipline. As such, various methods suitable to these two types of research activity set the foundations for this hybrid methodology. The aims and objectives have been divided into three key stages: Explore, Experiment and Evaluate. Overall, ten methods were selected to apply the outcomes of knowledge integration and achieve the objectives: Literature review, collaborative learning, visual thinking, creative play, experimental design, lab visits, interviews, consumer survey, presentation, and material testing. As with many aspects of this research, these methods are not independent but are intertwined, connected, and overlapping.

This section details the ten methods used across the three stages of Explore, Experiment, and Evaluate, followed by an in-depth look at the research structure, demonstrating how each method achieves the research aims and objectives. It should be acknowledged that these methods are utilised interchangeably throughout the research, and this section is just one of several instances where they are discussed and dissected.

3.4.1 Explore

This stage accounts for the literature review, mapping of stakeholders and material exploration. Significantly, this stage relies upon collaborative learning and early knowledge exchange through conversations, note-taking, and video tutorials. Visual thinking was also used to help disseminate the research, find common themes, and draw conclusions. Although visual thinking methods were used throughout the project, mapping and giga-mapping were essential at this stage when handling large quantities of data and establishing a successful research framework.

Literature Review

The literature review is structured into three main sections: “Materials from Milk,” “Disposability vs. Durability,” and “Transitioning to a Regenerative Economy.” This review aligns with the research objectives, offering a contextual foundation to define the scope and position the study within the existing knowledge regarding casein’s historical and future potential as a sustainable fibre source.

The historical aspect of this review explores casein materials in the 1930s-1950s through archival journals and patents. It delves into the factors contributing to the rise and decline of casein materials during that period, including societal, political, and technological influences. This historical context is pivotal for the “design by replication” process, wherein replicating existing casein fibre manufacturing methods helps comprehend the underlying chemistry.

Additionally, the literature review investigates early instances of fast fashion in post-war times, examining historical magazine articles, journals, and advertising campaigns. It also addresses contemporary fast fashion and the environmental and social ramifications of disposable products. Throughout this review, Rubbish Theory, as proposed by Thompson (2017), aids in identifying shifts in societal attitudes toward the value of fashion, textiles, and technology.

While critiquing these themes is crucial for understanding the context surrounding casein-based materials, the literature concerning regenerative systems and design frameworks underscores the review, facilitating connections between historical and contemporary perspectives.

Collaborative Learning

Collaborative learning was primarily established during the research's exploration stage, with Microsoft Teams as the central platform for communication. Online meetings served as a means for researchers to stay informed about each other's progress. Typically, these meetings included a brief update on ongoing work, its successes or failures, and clarifying questions, given the differing terminology between textile design and chemistry disciplines, especially in the early stages. This open forum allowed for sharing thoughts and ideas, with documentation through note-taking and recordings at various junctures to aid reflection.

Lab or studio photos and videos were shared for visual learning, particularly during material development. This visual approach was pivotal in the development of casein films. In this process, JH replicated the original method and shared relevant literature and visual tutorials, facilitating mutual learning. This two-way exchange was valuable, especially for a designer adapting to a new field, enabling the comprehension of novel techniques. This was reciprocated when creative work was shared to inform laboratory work, especially when working with commercial casein fibres and contributing feedback for material and development of the Experimental Skinninf Rig (ESR).

Visual Thinking

As a method, visual thinking complements other approaches by aiding information processing, theme identification, connections, problem-solving, and drawing conclusions. In the early exploratory phase, it played a pivotal role in project organisation and team communication within WP6. Mapping and giga-mapping exercises were employed using paper and pencil, electronic drawing tools, and software such as Miro, Mind Manager, PowerPoint, and InDesign.

In the later research stages, visual thinking became indispensable for effective outward-facing methods, such as presentations. Complex concepts and frameworks were represented through schematics, photography, and imagery when preparing presentations and written materials. During the design phase, mood boards were employed to gather and structure visual references. Various online platforms like Pinterest, Instagram, and Google, along with visits to exhibitions, museums, and art galleries, were used to gather references. The collected imagery was then organised and stored digitally or in a physical materials file.

3.4.2 Experiment

This stage focuses on developing casein-based materials, utilising food waste for colouring processes, and crafting a design framework for regenerative, mono-material disposable garments. Three primary methods employed were Creative Play, Experimental Design, and Lab Visits. Various reflective, collaborative, and visual techniques were utilised to document processes and evaluate material quality. These included maintaining a sketchbook and materials file, note-taking, photography, video calls, tutorials, and sharing material outcomes for feedback.

Notably, these methods were interlinked, evolving through an iterative process. Materials explored during Creative Play led to a broader understanding of the possibilities of casein, which helped to develop the Experimental Design process.

Creative Play

Initially, commercial casein fibres were explored through hand spinning to provide feedback to JH. This feedback informed the development of desirable fibre properties for lab-produced filaments and guided the design of the ESR (5.4.1). The experimental work was closely aligned with insights gained during the 'Explore' stage and continuously influenced the design approach. Each body of practice here followed a trial-and-error process and design by replication.

Casein films were also explored as an alternative direction (5.2.2), driven by lockdown challenges and limited access to facilities and equipment. Films were chosen for quicker production than fibres; the film-making process could then be applied to fibre production at a later stage. Collaborative learning techniques facilitated communication of the lab film development process, ensuring safe adaptation for home use. This involved substituting certain chemicals, like formic acid and sodium hydroxide, with safer alternatives. This home-based approach also allowed early exploration of colour using natural dyes.

Using colour extracted from food waste, a sustainable colouration method for casein-based materials was developed and tested on commercially purchased casein fabric, yarn, and home-produced casein films (5.3). Simultaneously, cross-linking agents were investigated by JH in the lab and later used to develop a wet-spun dyeing method for casein filament (5.4.3). Additionally, screen printing inks from food waste were formulated, experimenting with various natural or certified biodegradable printing mediums (5.3.5).

Finally, knitted (5.3.6) and woven (5.3.7) test samples were developed from commercially bought casein yarn. This process provided insights into the tensile strength and fibre-shedding characteristics of existing casein materials.

Experimental Design

Creative Play was followed by Experimental Design. This method differs from Creative Play by being purposeful and driven by specific questions developed in response to the outcomes of Creative Play. This method was informed by the ESR's development at UoL by JH, involving collaborative work on casein filaments in the lab (5.2.4) and a second weaving project in collaboration with HAG (5.4.4). These collaborative projects were informed by a final brief for a collection of mono-material regenerative garments made from casein-based materials (6.2.2).

Traditional fashion design techniques, such as sketching, pattern drafting, and pattern cutting, were employed. Various garment construction methods were explored, including zero waste pattern cutting and non-sewing techniques using casein glue, aiming for energy and resource-efficient construction that degrades quickly (6.3). After sampling a small range of garment shapes and styles, simultaneous design techniques (Townsend, 2003) were used to develop dyed and woven textile samples alongside designing a range of transient, casein-based garments (TCGs) (6.4).

Lab Visits

Lab visits marked the final stage of Experiment, characterised by collaborative practice involving UoL, Keracol, and myself. Initially, these visits were intended to be regular throughout the project but were delayed until early 2022 due to the pandemic. Consequently, they served as opportunities to compare lab-based processes for creating casein-based materials and dyes with the techniques developed at home and to conduct necessary equipment tests.

During a one-week placement at Keracol (5.3.4), I collaborated with Dr Alenka Tidder (AT) to dye casein fibre and fabric using anthocyanins from blackcurrant (BC) and avocado. Prior experience with dyes at home allowed for comparisons regarding achieved colours, colour stability, replicability, and colourfastness.

During a one-week visit to the Leeds Institute of Textiles and Colour (UoL), I divided my focus between using the ESR to test theoretical hypotheses derived from Creative Play (5.4.1). This experience was a pivotal chance to work in the same physical space as each other and to work more creatively together (compared to online meetings and tutorials). It also provided an invaluable opportunity to develop the scope for future transdisciplinary research projects.

3.4.3 Evaluate

Evaluation of material outcomes is iterative and takes two forms. Firstly, testing at UoL focused on determining the mechanical properties and suitability of the textiles produced for disposability and composting. Tensile testing (5.5.1), colourfastness testing (5.3.4), thermophilic testing and plant response testing (5.5.2) were conducted on both commercially sourced yarns and fibres. (Commercial fibres were tested initially as not enough filament could be produced in the lab to carry out this level of testing.) Secondly, outward-facing activities were conducted, including conversations and interviews between project partners, presentations and conferences, and a consumer-based survey (4.1). This stage of research draws on a more qualitative approach to determine and evaluate perceptions of 'quality', which feed back into the final design brief. The results of such methods were then used to create new discourse on disposability as a textile quality and to apply a new lens on a 4th generation of casein for use in the FTI.

Interviews

Three online interviews took place at various research stages to gain insights from individuals with specific connections to specific dissemination areas. The first interview, conducted by HAG, featured Joanne Silverstein (co-founder of DISPO) and Julia Meyersohn (daughter of Diane Meyersohn, co-founder of DISPO) focusing on the social and cultural context of the 1960s' paper dress' fashion trend (10.1.1) and the materials and processes used. This interview influenced the paper titled 'Challenging perceptions of fast and slow in contemporary fashion: A review of the paper dresses trend in the UK and the USA during the 1960s,' referenced in Chapter Two.

The second interview was with David Courtney from Courtney & Co, a UK manufacturer of casein buttons named Codelite, exploring their motivation to bring casein button production back to the UK and their sustainable approaches in a heritage industry (10.1.2). The third interview involved Professor Kate Goldsworthy (KG), known for her work on speedcycles with the Mistra Future Fashion Project and her role in the BFTT. This interview aimed to disseminate theoretical and practical work related to speedcycles and the future vision (Appendix 10.1.3).

These interviews were conducted as a part of the WP6 industry report and can be found in Appendix 10.1.

Consumer Survey

An essential part of the research was enquiring where and how RPFs might fit within our current fashion and textile systems. To do this, understanding consumer opinions and consumption habits was required. The research also showed that there is often a mismatch between garment durability and life expectancy. The consumer survey (4.1) sought to clarify terms including 'quality,' 'durability,' and 'disposability' in relation to clothing and to gauge consumer sentiments on these concepts.

The study had three objectives:

1. Understanding consumer views on textile quality and disposability
2. Examining consumption habits such as reasons for buying new clothing
3. Assessing how consumers typically dispose of clothing.

To ensure a broad demographic representation, a minimum of 100 respondents from various ages, genders, and backgrounds were surveyed.

Presentations

Presentations were a crucial part of the research's evaluation stages, facilitating feedback from peers with diverse backgrounds. Two independent presentations were delivered during the PhD as part of the University of the Arts Research Network. Collaboratively, eleven presentations were given as part of the BFTT, including the board of directors' meetings and other work package sessions. One independent presentation took place at the Waste-Me-Not online symposium, co-organised by Lauren Leal Junestrand, Dinu Bodiciu, and me through the LCF student hub.

One collaborative presentation was given at the 26th Annual Green Chemistry Conference in Reston, VA. Given my role as a fashion and textile designer, addressing audiences often from various disciplines, it was essential to deliver information engagingly and comprehensibly. Audience questions were a valuable gauge of presentation accessibility; questions centred on terminology suggested complexity, while insightful, context-related questions indicated understanding from the audience.

Finally, HAG and I presented aspects of the RDF at the 92nd Textile World Institute Conference (TWIC), focusing on the durability and design of woven casein samples. This presentation provided an excellent opportunity to gain feedback from textile industry experts on the more controversial aspects of the research regarding designing for short-term or single use.

Material Testing

Material testing was necessary to evaluate material properties in line with the RDF. The range of tests conducted included tensile testing (UoL), colourfastness (Keracol), thermophilic testing (outsourced), and plant response testing (outsourced). Tensile Testing was conducted to compare the strength of both dyed and undyed casein yarns (5.5.1). This added to the discourse surrounding the use of specific natural dyes as a cross-linking agent capable of affecting textile properties and functionality.

Colourfastness testing was conducted on both casein fibres and fabric to assess the suitability of natural dyes (blackcurrant skins) on existing casein materials (5.3.4). The results of this testing indicated the possible challenges of colouring lab-produced casein filaments with anthocyanins. Eurofins BLC Leather Technology Centre Limited carried out the final series of tests and investigated caseins' suitability as a compostable textile material (5.5.2/5.5.3). Both commercial casein fibres and lab-produced casein filaments were tested as proof of concept for transient, casein-based garments (TCGs).

3.4.4 Research Structure

Figure 34 presents each of the methods within the research structure. A pivotal moment during the experimentation phase led from a circular design to a regenerative design mindset. Each stage (explore, experiment/evaluate) is iterative and requires a flexible and reflective approach. Once a shift in priorities towards regenerative design was established, it was necessary to define the new brief with project partners/collaborators and conduct a second literature review in this field of study. This way, the research structure continuously evolved and adapted to new discoveries.

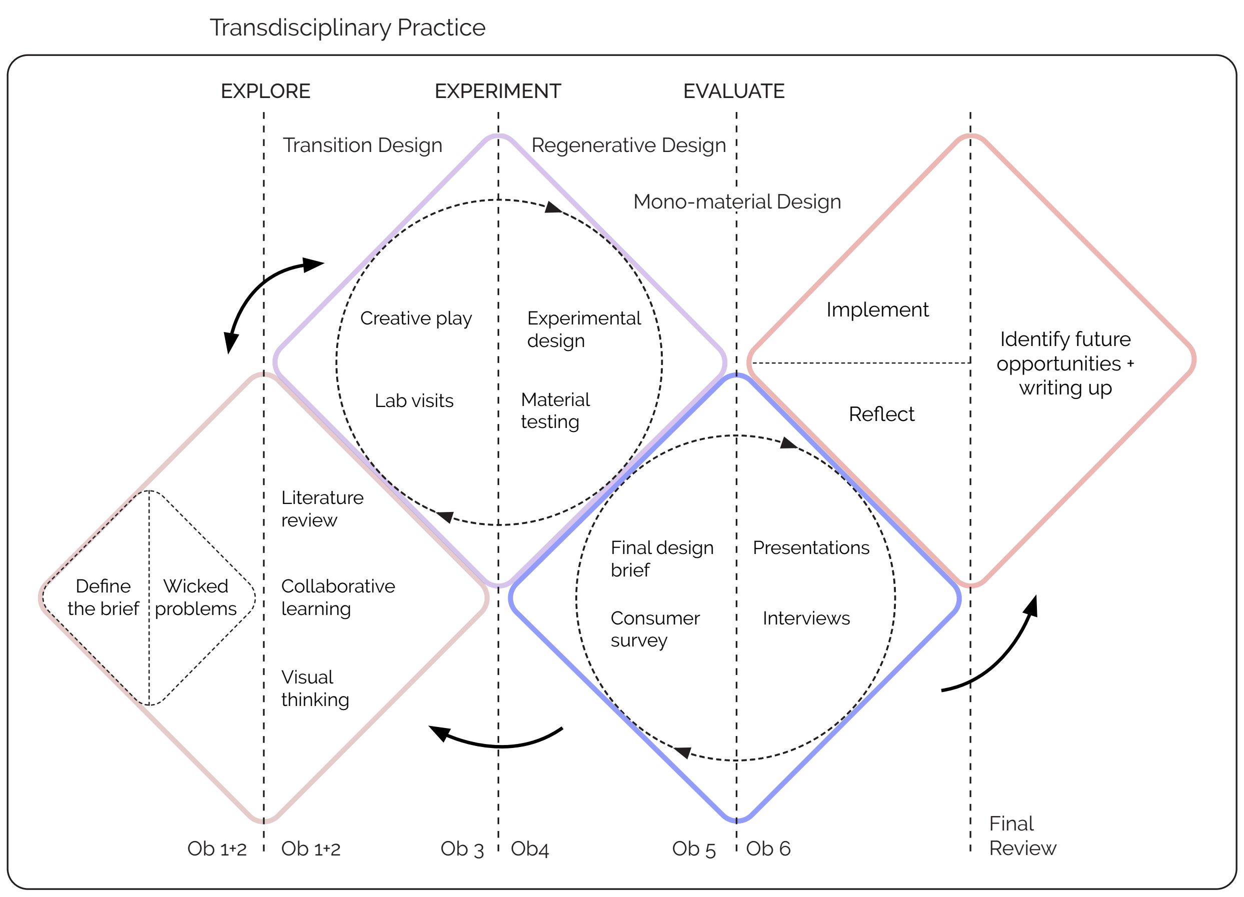


Figure 34: Mixed methodology research framework

Table 7 breaks the methods up within each section and presents them against the research aims and objectives.

Aim	Objective	Phase	Method	Action	Chapter
To advance the understanding of casein fibre processing for its integration into a regenerative fashion economy through knowledge integration.	To document contemporary and historical textile practices concerning regenerated casein fibres and other protein-based textile materials, delineating the techniques employed and the resources utilised. To map the origins and implications of disposability within the context of speedcycles and offer a multidimensional perspective on this phenomenon.	Explore	Literature Review		2
			Collaborative Learning	Note taking, Photography, Video calls, Lab reports, Tutorials.	2-5
			Visual Thinking	Mapping and giga mapping.	1-8
To establish an effective transdisciplinary methodology encompassing design, green chemistry, and archive data, facilitating the generation of novel insights in processing casein for regenerative textiles.	To undertake a thorough critical review of casein-based materials within a regenerative design framework, incorporating Living System Principles (LSP) principles. To leverage insights gained through the transdisciplinary process to guide the design and fabrication of textil artefacts that exemplify casein materials' aesthetic and functional characteristics within regenerative fast fashion.	Experiment	Creative Play	Playing with casein, Playing with colour, Playing with fibres, Playing with yarn. Natural dye workshop.	5
			Experimental Design	Experimental Spinning Rig, Development of casein filament, Woven Textile Design, Mono Material Garment Design.	5-6
			Lab Visits	Lab visit 1: Keracol, Lab visit 2: UoL.	5
Critically examine and evaluate prevailing perceptions of regenerative principles and disposability as quality indicators within the fashion industry.	Engage with stakeholders to understand preconceptions of garment quality and critically evaluate 'the vision'. To engage in a comprehensive critical reflection, drawing upon the outcomes of the evaluation process and findings, thus contributing to the ongoing discourse in regenerative design.	Evaluate	Interviews	Interview 1: Dispo, Interview 2: Courtney & co, Interview 3: Prof Kate Goldsworthy	Appendix 10.1
			Consumer Survey	Consumer survey.	4
			Presentations	BFTT presentations, 'Waste-Me-Not': UAL, 26th Annual Green Chemistry Conference, TWIC.	3
			Material Testing	Tensile testing, (UoL) Colourfastness, (Keracol) Thermophilic testing (Outsourced), Plant Response testing (Outsourced).	5

Table 7: Methods and Research Structure

3.5 Summary

The research articulated in Chapter 3 sought to explore the application of a mixed methodological approach combining transdisciplinary research, transition design and regenerative design methods. Combining such systems-based approaches was necessary to transition from a product-based mindset to a system-based mindset as they each encourage the visualisation of the bigger picture or world view, accounting for all stakeholders and holistically addressing impacts throughout the supply chain. Using tools such as the regenerative design wheel (Figure 32, p73) to aid this process, key themes and stakeholders can be matched with areas of the supply chain, and impacts can be visualised, questioned, and challenged throughout the research to identify opportunities for intervention and improvement.

Each of the ten methods used was selected to aid the transdisciplinary research process between JH, HAG and myself by forming a shared definition of the research problem and a future vision for which to aim. To view each researcher's contributions equally, design methods such as creative play and experimental design allow for a flexible, trial-and-error approach where all results are seen as a positive contribution to knowledge, and any 'failed' experiments are not viewed as a setback. Methods such as interviews, presentations and surveys also allow the opportunity to disseminate the research with consumers, industry experts and researchers, providing scope for future research.

A regenerative design framework for transient, casein-based garments capable of addressing the research objectives was created and has been used to inform and guide the research going forward. Mono-materiality has also been identified as a method of regenerative design suitable to the application of casein-based garments due to the ability to convert casein into a range of textile and non-textile materials.

4

UNDERSTANDING PERCEPTIONS OF GARMENT QUALITY

Throughout this study, the transdisciplinary approach has shed light on critical issues surrounding the contemporary definitions and criteria for assessing quality, sparking new discourse within this domain. Additionally, the literature review has emphasised the necessity for a deeper understanding of consumer expectations regarding the durability and longevity of specific garments. For instance, it was revealed that, on average, clothing items are discarded after ten wears, as reported by the "Pulse of the Fashion Industry" in 2017. However, this statistic fails to clarify the anticipated lifespan of individual garments, such as t-shirts, jeans, or dresses.

Access to such specific information holds significance for guiding designers in setting durability benchmarks for distinct clothing items and strategising ways to engender a cultural shift in perceptions of textile quality and durability.

This chapter delves into consumer attitudes and beliefs concerning garment quality and longevity, beginning to assess the theoretical findings (Chapter 2) and methodological framework (Chapter 3). This insight serves as the foundation for creating a holistic and speculative vision that informs the research going forward and serves as a recurrent point of reflection throughout this thesis.

Two interviews, conducted as a part of an industry report for the BFTT (WP6), also informed the development of this vision. An interview with Professor Kate Goldsworthy was conducted for an academic viewpoint on the RDF, and an interview with David Courtney from Courtney & Co was conducted from an industry viewpoint on manufacturing with casein in our current society.

4.1. Addressing Gaps In Knowledge: Consumer-Based Information

This section provides an overview of the findings derived from the consumer survey investigating perceptions of textile quality and the disposability of garments. The primary objective of this survey was twofold: firstly, to enhance our understanding of the potential prospects and obstacles associated with the adoption of regenerative, short-lived garments, and secondly, to bridge knowledge gaps pertaining to real-world consumer needs by distinguishing the interplay between consumers' perceptions of garment quality, their purchasing behaviours, and their garment disposal rates.

As an anonymous online study, this survey engaged a diverse cohort of 120 participants from varying demographic backgrounds. Participants were tasked to complete 11 tick-box-style questions centred around their perspectives on textile quality and disposability, divulging their shopping patterns and practices related to garment disposal. The survey was designed to juxtapose responses regarding preconceptions of disposability with actual buying and disposal behaviours. Additionally, it sought to ascertain the expected lifespans of different garment types. This survey employed an exploratory approach characterised by the use of mixed-method strategies. This multifaceted methodology was instrumental in unveiling nuanced perceptions concerning garment quality, disposability, and the anticipated lifespan of clothing items. Furthermore, it facilitated the examination of consumers' cognitive linkages between these factors and their attitudes towards sustainability.

4.1.1 Method

Responding to gaps in knowledge regarding textile quality and disposability, this survey aimed to gain insights into four key areas:

- Understanding Consumer Perceptions: The survey set out to uncover consumer opinions concerning textile quality and the disposability of clothing items.
- Exploring Consumption Habits: It sought to delve into consumption habits, including the motivations behind purchasing and disposing of clothing.
- Assessing Disposal Practices: The survey aimed to understand how consumers typically dispose of their clothing once it reaches the end of its utility.
- Anticipating Garment Lifespans: A critical objective was to ascertain consumers' expectations regarding the expected lifespan of specific clothing items.

The survey was conducted online in 2022 and was circulated via email through BFTT and UAL

networks and social media to reach a varied audience. The survey comprised 11 questions, grouped into two broad areas: consumption habits and garment expectations. The research blended qualitative and quantitative methods, employing open-ended and closed-ended questions to provide an in-depth examination of the perceptions and attitudes towards garment quality and life expectancy. While the survey was structured with tick-box responses, specific questions were designed to allow participants to provide clarifications or explanations as needed.

In terms of demographics, participants were asked to disclose their age and employment status to identify any potential correlations regarding consumption habits and garment expectations. No other demographic questions (such as gender, occupation, or income) were asked as this information was unnecessary to meet the study's aims.

Questions were tailored to explore participants' motivations for purchasing and disposing of clothing. Respondents were also prompted to express their sentiments towards terminology like 'disposability,' 'durability,' and 'quality,' examining how these terms were perceived in relation to sustainability, whether positively or negatively. The final section of the survey focused on gauging how long participants expected specific garment types (Coats, dresses, jeans, shirts, T-shirts, and underwear) to remain functional, ranging from one month to ten-plus years. This structured approach allowed for meaningful comparisons between shopping behaviours and individual clothing items' envisaged durability and longevity.

For a complete list of questions and responses, see Appendix 10.2.

4.1.2 Survey Results

The findings from this survey provide valuable insights into the alignment of individuals' consumption patterns with their expectations regarding garments. The data obtained was analysed using quantitative and qualitative approaches. Thematic content analysis was applied to scrutinise qualitative text data and identify emerging themes and variables.

Transcripts were reviewed line-by-line and then organised via open coding to identify themes and compare the connections with the other categories (Hur & Cassidy, 2019).

Results are initially explored question-to-question and then cross-referenced to quantitatively analyse the relationship between multiple variables. This multifaceted analytical approach ensured a thorough examination of the survey data and a comprehensive understanding of the nuanced relationships between consumer behaviours and garment expectations.

Q 1: How old are you?
Regarding participant engagement, 50% of respondents were aged 26-35, and 26.7% were aged between 36-46.

Q2: Which of the following categories best describes your employment status?
Most participants were in full-time employment (68.3%), with significantly fewer (11.7%) in part-time employment, students (8.3%) or self-employed (6.7%).

Q3: On average, how many items of clothing do you buy in one month?
On average, participants claimed to purchase '1 or fewer' new items of clothing a month (56.7%), with '2-4 items per month' second (37.5%) and '5-7 items per month third (5%). Only one respondent claimed to purchase '8-10 items per month' (0.8%), and no respondents claimed to purchase '10+ items per month'.

Q4: What is your main motivation for buying new clothing?
When questioned on their motivation for purchasing new clothing, 'Replacing worn-out garments' came first (46.7%), with 'For a specific occasion' a close second (45%). After this, the response, 'I buy clothes when I need to' (22.5%) and 'Other' (19.2%) were also close. Out of the 23 respondents who selected 'Other', motivating factors such as 'Sales', 'The buzz of having something new' and 'Refreshing my wardrobe' were most common, suggesting that purchases of new items are primarily impulsive. Some respondents listed alternative motivating factors such as 'Gender transitioning' and 'For a growing infant', with only one respondent stating, 'I haven't bought any clothing this year and don't plan on it for the rest' as they had set a personal goal to do so.

Q5: What is your main motivation for discarding clothing?
When questioned regarding clothing disposal, over half of the participants (55%) stated that 'Poor quality or broken' was their primary motivation, with 'no longer fits' second (44%). An equal number of participants responded with 'No longer in style' and 'To make room for new clothing' (23.3%). Fewer participants responded with 'Other' (10.8%); however, they specified reasons such as 'Worn out' and 'Does not fit right' or 'No longer suits me'.

Q6: How are you most likely to discard your clothing?
Regarding disposal methods, most respondents donate their garments to charity (65%). After this, responses drop down to 'Use of textile recycling bins' (16.7%), 'Other' (13.3%), With general household waste' (3.3%%) and 'I upcycle my garments' (0.8%). Of the 16 respondents who answered 'Other', 12 said they either sell online or give to friends and family. The remaining four stated to either upcycle, fix or repair garments where possible, use them as rags or recycle them through H&M's in-store garment recycling scheme.

Q7: What do you most associate with high 'quality' clothing? (Order of importance from 1-5)
The following questions move on from consumption habits and investigate mindsets and associations surrounding terminology and garments. Respondents mostly associated well-made clothing and durable materials with high quality, selecting on-trend clothing last, stating that 'Clothes should be made to last but also make you feel good in them, better materials and well-made clothes fit better and therefore kept for longer periods or still good quality to be sold 2nd hand'. Again, this suggests more consideration and care might be taken in selecting their clothing, which is purchased more as an investment.

When asked to rank answers regarding what they most associate with 'High-quality clothing, 'Well made' came first, with 'Durable materials' second, 'Fit for Purpose' third, 'Expensive' fourth and finally, 'On trend' was voted fifth.

Q8: Do you associate high-quality clothing with sustainability?
In terms of associating high-quality clothing with sustainability, participants were asked to explain their answers in more detail. Most stated that they 'Sometimes' associate high-quality clothing with sustainability (52.5%).

46 out of 120 (38.3%) comments discuss a positive association between quality, sustainability, and longevity.

"I believe better quality clothing lasts longer, and as such, I buy less." (Respondent 22)

"Sustainability means it will last longer and therefore constructed better." (Respondent 32)

"Because if it has high quality, it will last longer; thus, it is more sustainable." (Respondent 87)

Comments like these were widespread, perpetuating the idea that slow fashion is more sustainable (sometimes regardless of material or other contributing factors). Some participants also appeared dubious of high-quality fashion, stating that some designer and high fashion brands are still stuck in the '*seasonal nature of fashion*' (Respondent 13) and voicing their concerns about greenwashing (Respondent 86 & 119).

Q9: How important is durability when choosing an item of clothing?
Continuing from Q8, Q9 asks participants how vital durability is when choosing clothing. All respondents stated durability was of some level of importance, with most selecting that durability was 'Moderately' important (durable items are purchased when possible but are sometimes unaffordable) (60.8%), whilst 'Slightly' important (durability is preferable but not prioritised over style) (21.7%) came second and 'Very important (selected over style and cost) (17.5%) was appointed the least. (0% of respondents said durability was not a priority.)

Participants who chose to explain their answers reiterated longevity as a motivating factor for prioritising durability (38.3%), stating it is desirable for clothing to last as long as possible and to launder well (not lose its shape or colour, etc., over time) which in turn reduces the overall amount of clothing they purchase. Respondents also discussed circumstantial factors such as fitness for purpose, varying requirements across different garments, and cost as barriers to purchasing more durable clothing.

Q10: How does the term 'Disposable' make you feel?
Moving from durability to disposability, participants were asked how the term 'Disposable' makes them feel. The vast majority responded with 'Uncomfortable' (45%), then 'Angry' (25.8%) second, and 'Unsure/I don't feel strongly either way' third (22.8%). Few responded with 'Other' (5%), and only 1 participant responded with 'Positive' (0.8%). All participants were asked to explain their answers to this question:

For those who responded with 'Other' reasons were listed as:

"Uncomfortable when it comes down to clothing. In another context, it might not be so negative." (Respondent 27)

"It is part of the market economy we live in; if the governments of the world don't tackle single-use items, why should I, the individual, have to deal with negative feelings?" (Respondent 48)

"I could easily imagine disposable underwear, as long as it is of natural materials. Other items of clothing, it's more difficult." (Respondent 62)

Although most participants felt pessimistic about the concept of disposability, there was a general sense of conflict surrounding the term. Some participants openly acknowledged their part, stating, "I hate the idea that we throw so much away but recognise I am part of the problem" (Respondent 8) and "I don't like how many of my items can just end up in landfill! However, I seem to choose more disposable clothing as it tends to be cheaper." (Respondent 34)

One participant went into further detail surrounding their conflict of disposability, acknowledging that eventually, everything must be disposed of and that we must create better outlets in terms of circularity for when this inevitably happens:

"It's a hard one. If we move towards a circular system where waste textiles can be made into new fibres, then we can manage textile waste and disposable items a little easier. It's not the ideal solution at all, but it would allow fashion to remain (to some extent) 'fast' for some markets and help manage overconsumption and unchanging consumer attitudes.

It would also provide an outlet for waste textiles that eventually cannot be worn again through wear, which is inevitable. I think we need to promote 'make do and mend' because things can be sewn back if they break; even fast fashion can be kept in circulation. Clothing can be kept in the use phase for longer, even if it's cheaply made, if consumers are engaged with sewing and donation activities. But eventually, that item of clothing will need to be disposed of. And we need an outlet for that." (Respondent 49)

Q11: On average, how long do you expect each of the following items to last:
For the final question, participants were asked how long they expected different kinds of garments to last. On average, coats had the most extended expected lifespan, with most respondents (31.7%) selecting +10 years. For dresses, most respondents expected a useful lifespan of 4-5 years (33.3%). However, for the other garments listed, 2-3 years were most expected (Jeans: 34.7%, Shirts: 43.2%, T-shirts: 51.2%, Underwear: 54.9%).

Only a few participants selected '1 month or less' for any garment (Shirt: 0.8%, T-shirt: 1.7%, Underwear: 0.8%).

Cross-Tabulation Of Results

Responses to several questions were cross-tabulated to gain a more comprehensive understanding of these results. Specific terms and vocabulary used by participants were also investigated to identify critical themes; for example, how many respondents referenced composability, biodegradability and garment longevity in their answers was noted.

Out of 120 respondents, only three referred to biodegradability or the decomposition of materials throughout the entire survey (Respondents 62, 69 & 99), generally stating that 'Things that are disposed of should decompose' (Respondent 69). More commonly, terms such as 'waste' and 'landfill' were used in answer to question 10 in reference to their discomfort or disapproval of disposable items, with the association that disposable items are wasteful and generally end up in landfills.

Upon analysing individual responses to the survey as a whole and cross-tabulating results, there were mixed responses and correlations between answers regarding intention and behaviours. For example, respondent 103 (aged 26-35) stated that they purchased one or fewer clothing items per month, but their primary motivation for doing so was for a specific occasion. Regarding garment disposal, respondents' primary motivation was to make room for new clothing, but they were most likely to do so by throwing away with their general household waste.

So far, this paints a mixed picture of someone who has considered their purchasing decision and is less likely to buy impulsively. However, being one of the few respondents to dispose of garments with their household waste demonstrates less consideration towards sustainability or landfill waste.

When cross-comparing respondents' motivations for purchasing new clothing (Q4) with their motivations for disposing of clothing (Q5), there was a clear correlation between the replacement of worn-out garments and the disposal of poor-quality garments (35.3%) (chart 1). These results demonstrate that functionality and poor garment quality are significant motivating factors in consumption habits and that more durable garments could play a part in reducing consumption of this kind.

However, the second highest correlation was between purchasing items for a specific occasion and disposing of items as they are no longer in style or they are bored with the item (34.6%). This suggests higher style and aesthetical motivations over functionality. In such cases, durability becomes less critical as garments will likely be worn less and disposed of quickly.

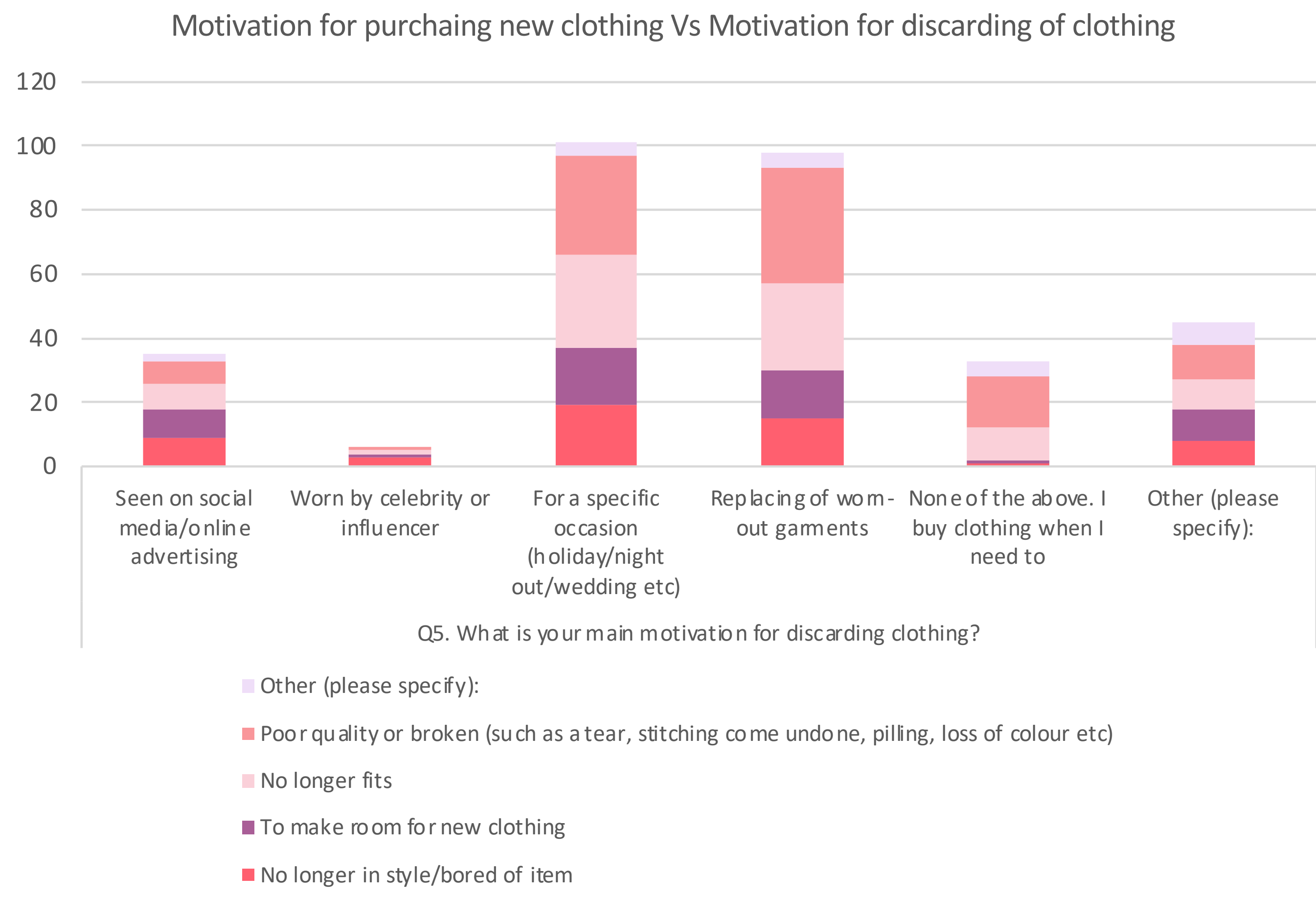
To gain a more detailed insight comparing intention and behaviour, the number of items purchased per month (Q3) was cross-tabulated with respondents' feelings regarding disposability (Q10). Again, the results were conflicting and, in some circumstances, highlighted a displacement between consumption habits and emotion (Chart 2).

The strongest correlation was between those who felt uncomfortable with the term disposability but purchased 2-4 items per month. Out of those who bought 2-4 items per month, 55.7% felt uncomfortable with the term disposability, 26.7% did not feel strongly either way, and 15.6% felt angry. Compared to those who purchased one or fewer items per month, 41.2% felt uncomfortable, and 30.9% felt angry. So far, this demonstrates that those who purchase less are likely to feel more distressed by the concept of disposability.

Of those who purchased 5-6 garments monthly, most respondents still felt angry with disposability (50%), suggesting there is more of a disconnection between intention and behaviour. Although we cannot assume that respondents who purchase more monthly clothing are likely to dispose of their clothing at the same rate, they are expected to have garments that remain unworn or are worn less frequently.

Those who tended to purchase more new clothing (Q3) were also more motivated to do so (Q4) by factors such as 'for a specific occasion' or 'seen on social media'. In contrast, those who purchased one or fewer items were motivated mainly by replacing worn-out garments (Appendix 10.2, p354).

In terms of durability, the number of items purchased per month (Q3) had little effect on the importance of durability (Q9). It was expected that those who purchased more clothing might find the durability of garments less important; however, all respondents stated that durability was of some importance to them, and those who purchased higher amounts of clothing still discussed the desire for clothing which is made to last (Appendix 10.2, p360).



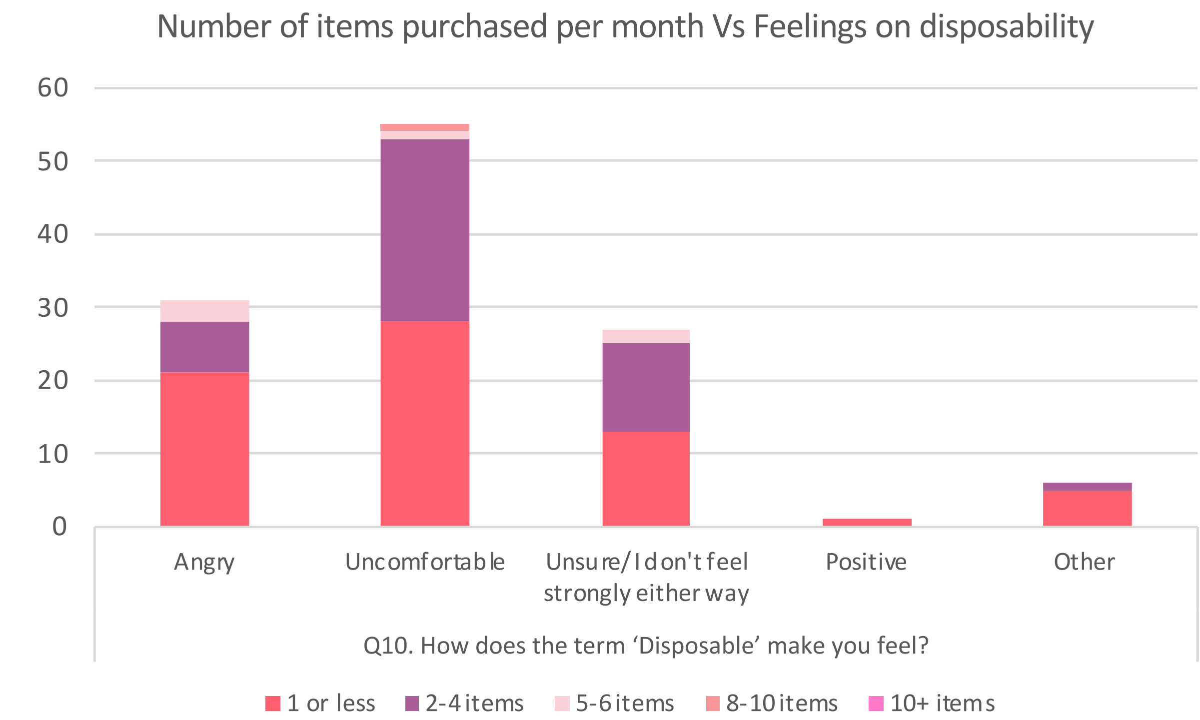


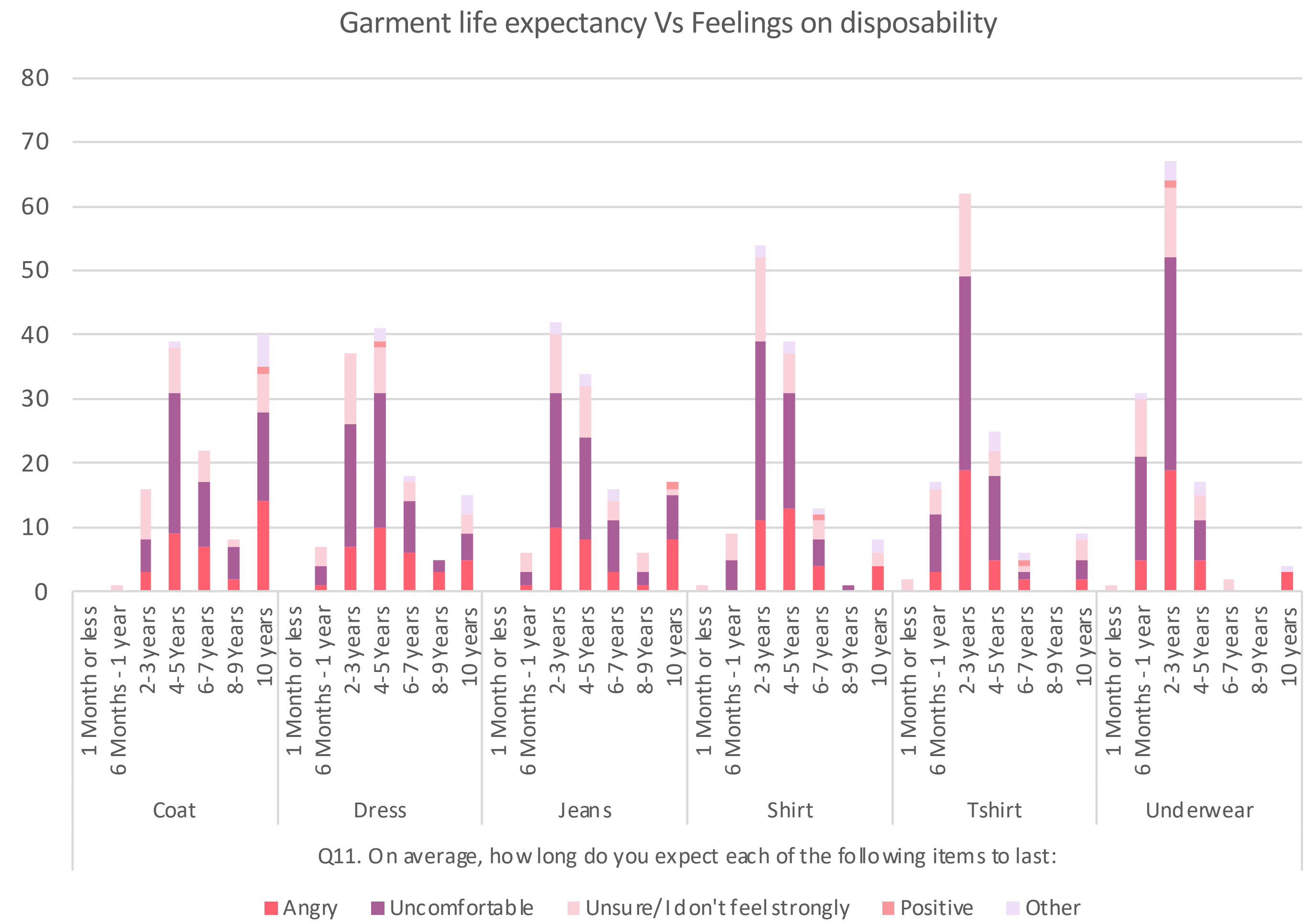
Chart 1: (Top) Motivation for purchasing new clothing Vs motivation for discarding of clothing.
Chart 2: (Bottom) Number of items purchased per month Vs feelings on disposability.

Regarding garment life expectancy, charts 3 and 4 cross-compare garment expectations (Q11) with the importance of durability (Q9) and feelings towards disposability (Q10). As discovered when comparing the number of items purchased with the importance of durability, there was little correlation to suggest that respondents consider garment durability in line with life expectancy.

Here, I expected to see those who felt strongly about durability and considered it 'very important' to select longer life expectancies for garments. This was the case for coats, where 50% of people who considered durability 'very important' expected a lifespan of 10+ years. For all other garments, however, life expectancy (generally seen as 2-3 years) had little correlation to the importance of durability (chart 3).

Similar to the cross-tabulation of questions 9 and 11, there was little correlation between feelings of disposability (Q10) and garment life expectancy (Q11). For example, those who favoured slow fashion and felt 'Angry' and 'Uncomfortable' with disposability still often demonstrated a generally low garment life expectancy.

Coats and jeans stood out as examples where life expectancy was longer, and respondents displayed stronger feelings against disposability (40% of respondents who felt angry about disposability expected coats to last 10+ years, and 25.8% expected jeans to last 10+ years.) For all other garment categories, a 2–3-year lifespan was generally expected despite feelings towards disposability.



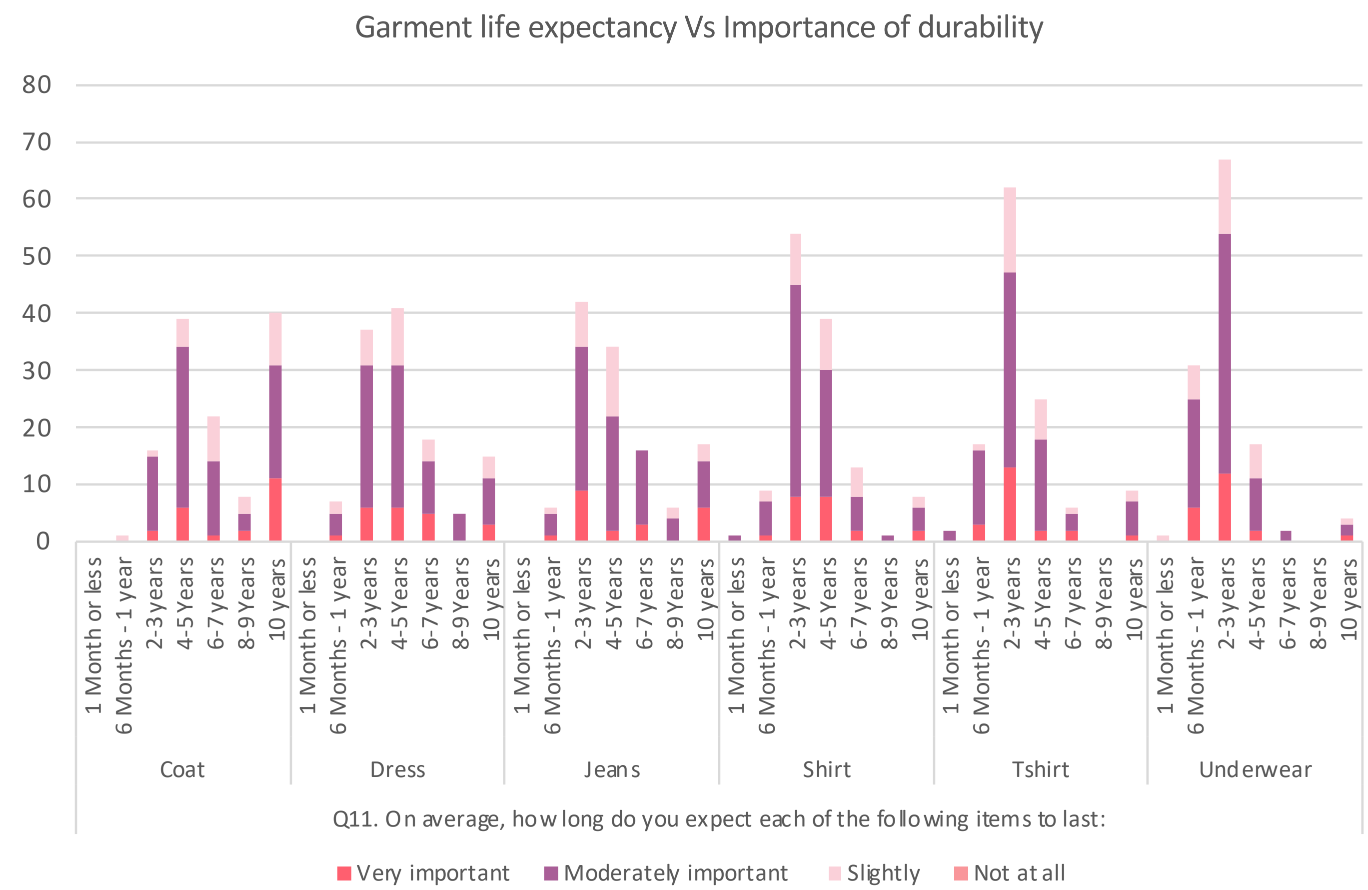


Chart 3: (Top) Garment life expectancy Vs feelings on disposability.
Chart 4: (Bottom) Garment life expectancy Vs Importance of durability.

4.2 Discussion Of Results

This survey of 120 participants was a valuable source of information towards understanding consumer needs and expectations. The results discussed present a journey from intention to action between participants, highlighting critical themes of interest, connections, and various paradoxes between areas of 'sustainability'.

Throughout the survey, longevity stood out as a critical theme connecting durability and sustainability, highlighting the expectation that well-made clothing (constructed to last longer) is seen as more sustainable through reduced consumption. However, when compared to common answers to questions regarding the consumption, disposability and life expectancy of garments, participants still often expressed a desire for newness or the need to keep up with current trends, with the second highest motivation for purchasing new clothing being an event or one-off occasion (after the replacing of worn-out garments).

Despite participants' awareness of sustainability and the connection between longevity and quality, it was highlighted that garment life expectancy was surprisingly low. Two to three years was the most common life expectancy of most garments (with coats and dresses expected to last longer), demonstrating a disconnection between the concept of longevity and longevity itself. It could be argued that consumers genuinely want garments of high quality and durability to last them longer and reduce the need to purchase new clothing, but we (as a society) still consider longevity within the narrow terms of our own lifespan and not what will happen to these garments once we can no longer wear them. For slow fashion to effectively reduce environmental impact and one's individual carbon footprint, we must consider longevity in terms of lifetimes, not seasons, years or even decades.

Recyclability and the passing on of garments (either to friends and family or through resale/donation) were also common themes regarding durability, as many respondents spoke about recycling and the likelihood of keeping garments in circulation post-use. Of course, this is a positive step and a huge leap in demonstrating adaptability and willingness to change behaviours to reduce environmental impact.

However, it can still be argued that passing garments on or donating to charity simply delays the inevitable journey to landfill or incineration. Also, not everything donated to charity shops is suitable for resale. It is reported that only 30% of donations are resold within the UK due to garment faults and low garment quality (House of Commons, 2019). It is also reported that some charities are charged hundreds of thousands of pounds per year to dispose of unsellable items (Hinde, 2020). With consumption set to increase 63% by 2030 (House of Commons, 2019), what does this mean for items that are damaged or unsaleable at the end of life?

Overall, these results have allowed some conclusions to be drawn regarding consumer mindsets and have highlighted areas for further investigation or deeper discussion. The disconnection between certain behaviours regarding sustainability and consumption, along with many participants' conflicts of emotions in terms of durability and disposability, suggests there is potential for consumers to adapt to new understandings of sustainability and consumption habits.

Although longevity offers one route to reducing impact, the results of this survey have demonstrated the complex relationship between consumption, motivation, and mindset. In terms of slow fashion, there is still the issue of damaged garments that cannot be resold, or that simply do not reach the recycling bins. As governments, foundations, and charities have incentivised recycling and resale, similar efforts should be made to encourage regenerative systems at different speeds.

4.3 An Evidence-Based Vision

Based on the research so far, the final section of this chapter defines an evidence-based, speculative vision for the future of fashion within a regenerative industry and economy. This vision has been essential to steering the practice and outcomes over the following two chapters.

The vision for this project explores the eventuality that textile materials and garments are designed to match their useful lifespan. Fast fashion is made from fast materials (quick to produce using minimal resources and energy), and slow fashion is made from slow materials (such as recycled materials or materials that require additional finishes or processes). Still, both can offer something at the end of their lifecycle. This could be through composting and providing nutrition to the soil or through recycling or regenerating into new textile fibres. In this vision, virgin materials such as polyester are phased out in favour of regenerated and recycled materials, creating new value in local waste streams within and outside the fashion and textile industry.

In this light, additional fashion and textile processes, such as colouration, woven structure, and garment construction techniques, are all considered factors when assessing the speed at which a final product is to be consumed. Specialist techniques are designed to aid the suitable process (such as composting or recycling) at end of life to recapture as much value as possible to be put back into the supply chain or nourish the earth. Alongside this, local governments and businesses work with consumers to help recapture this value. Textile waste collection schemes are vital to the success of this vision, ensuring that items that have fulfilled their purpose and come to the end of their designed lifespan are disposed of responsibly and continue to be repurposed or regenerated.

Following the RDF for TCGs, Figure 35 demonstrates this future vision by highlighting the basic transfers of value between local suppliers of agricultural and food industry waste, manufacturers, retailers and eventually, consumers. The potential stakeholders are also noted at each possible transfer, considering how they might influence or support the process. Where value is to be recaptured post-use, governments, local councils, designers, and retailers would be responsible for providing garment collection schemes to ensure value is redistributed, allowing maximum efficiency. For example, if a garment can be recycled into a new garment, or the brand wishes to keep the material value within its own supply chain, it would be the designer or retailers' responsibility to retrieve those garments post-use. If, however, the garment is to be composted (industrial) or put back into an agricultural supply chain, this might be the responsibility of a local council.

This model is reflected upon and strengthened throughout the practice-based research and material testing stages whilst considering the key themes and areas of impact as outlined in Section 3.2.2

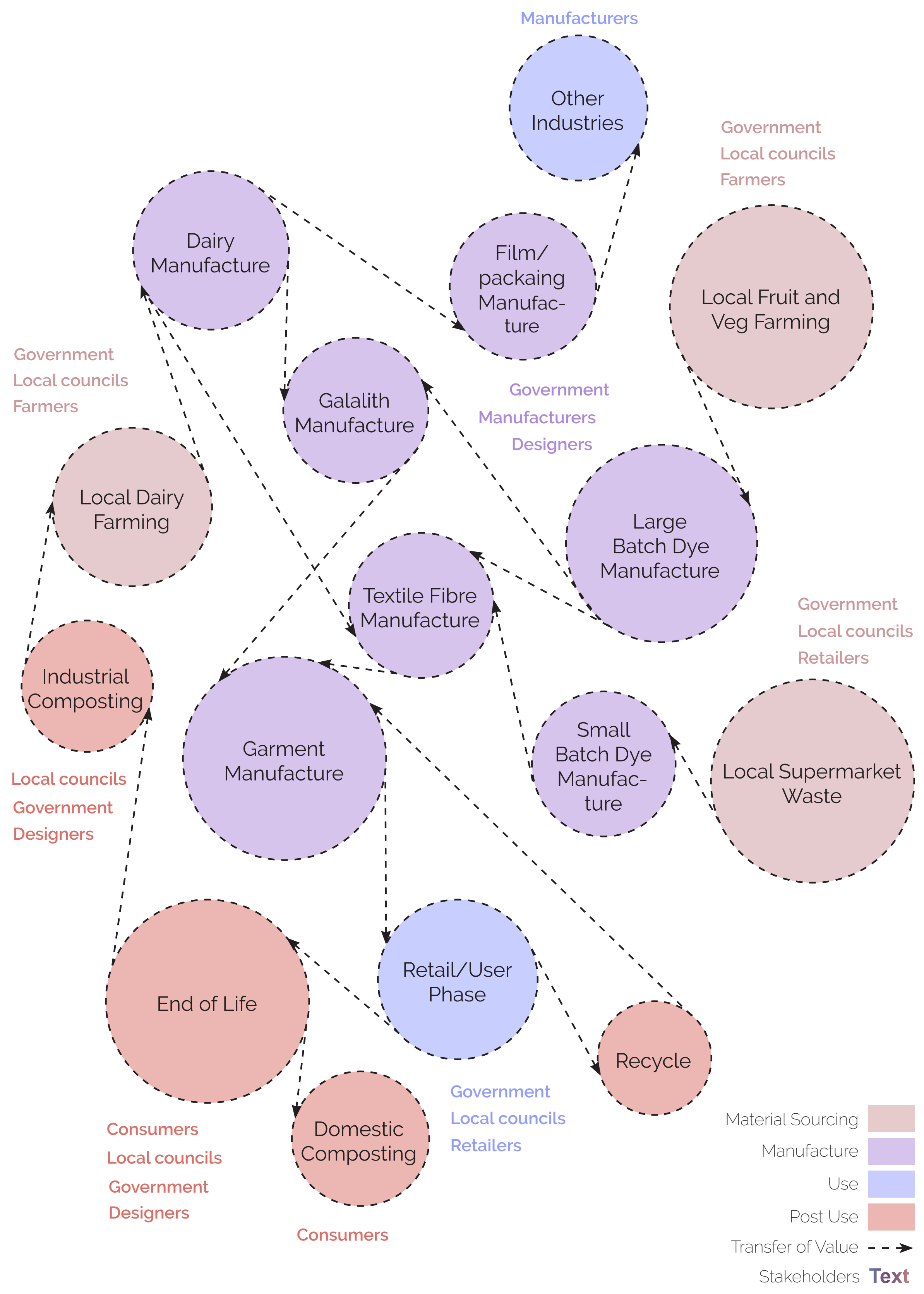


Figure 35: Demonstrating the future vision of a regenerative local economy for transient, casein-based garments.

4.4. Summary

This project investigates what quality really means within the fashion and textile industry and where value is placed within the supply chain in reflection of different speedcycles. The constant expectation that highly durable and long-lasting materials and garments are superior (and more eco-friendly) limits our understanding of what we truly need from our textile products. By redefining the positioning of quality from a durability standpoint and asking, "What value can this garment offer at the end of its life?" we can rewrite the narrative of what is expected from our everyday materials.

The Consumer survey has played a vital role in contributing to the overarching vision of this project. Through these interactions, valuable insights were gained about consumer preferences, perceptions of quality, and expectations from fashion and textile products. The survey data provided a comprehensive understanding of consumer attitudes towards durability, sustainability, and end-of-life considerations. Additionally, industry interviews (Appendix 10.1) allowed researchers to explore the perspectives of key stakeholders, including designers, academics, and manufacturers, shedding light on their current practices and challenges in implementing more sustainable approaches.

This chapter effectively addressed one of the key gaps in knowledge. By gathering information directly from consumers and industry experts, the project gained a realistic and current understanding of the prevailing practices and perceptions in the fashion and textile industry. This helped bridge the gap between theoretical research and real-world application, providing a more nuanced view of quality and value within the supply chain.

Despite the progress made through this chapter, some questions still need to be answered, and further research is required to explore the potential barriers and drivers for consumers to accept more responsible consumption habits and regenerative fashion models.

Another aspect requiring more attention is the long-term impact of regenerative approaches on the entire supply chain. While the project has redefined the positioning of quality from a durability standpoint to consider end-of-life value, it is necessary to delve deeper into how this shift can be integrated into industry operations and the potential economic and social impacts this might have.

Figure 36 demonstrates the workflow model for 'problem identification', achieved through transdisciplinary research. At this point in the thesis, the overarching problem has been identified and shared between researchers. The next chapter moves into the practice-based investigation, exploring methods of material development and decorative techniques within the scope of the vision.

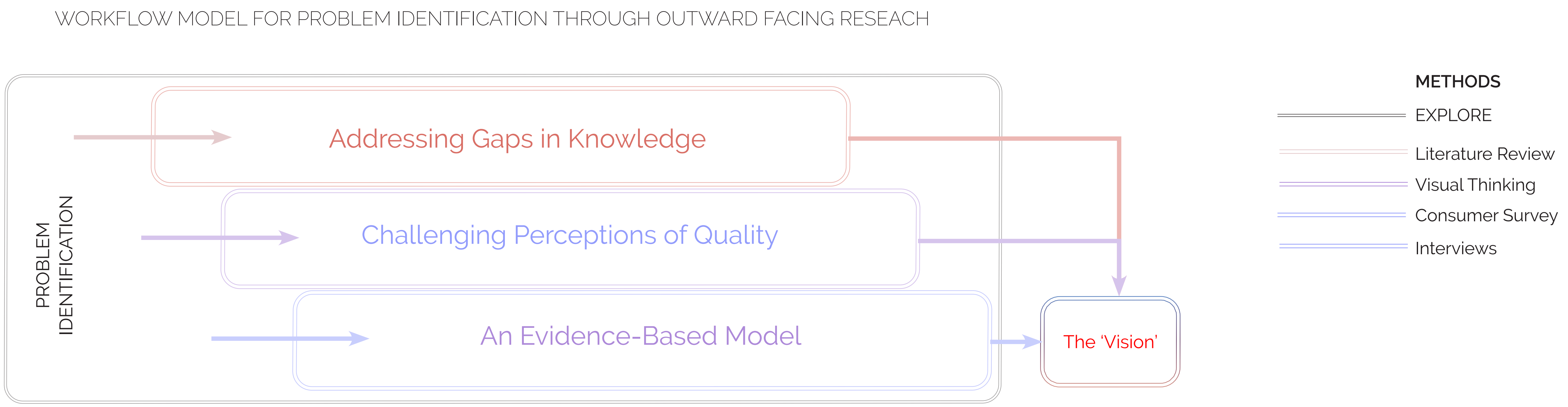


Figure 36: Workflow model for problem identification through transdisciplinary research.

5

Practice 1: Exploration Of Casein-Based Materials & Colour

“*To truly understand a thing, you have to make a version of that thing”*
(Dormer, 1997: p.18).

The early exploration of casein-based materials and colour was driven by the need to gain a first-hand understanding of their properties. At this stage, the principles of durability and quality within fashion were under scrutiny, and the concept of mono-materiality was at the forefront of the investigation. By understanding casein's natural properties and behaviours, potential opportunities for its application in a transient, regenerative fashion market have been identified. With objectives 3 and 4 in mind, this study has established a transdisciplinary collaboration process with JH and HAG to advance knowledge on the re-appropriation of textile techniques within the realm of green chemistry.

This chapter addresses gaps in the existing literature, particularly the need for more technological data on RPFs, and seeks to answer the key questions raised in Chapter Two: Is casein a suitable raw material for producing regenerative fashion?

The experimental research was conducted in collaboration with JH and HAG, with support from the external company Eurofins BLC Leather Technology Centre Limited, which was responsible for testing the compostability of specific casein materials. The research is divided between an exploration of casein as a raw material (5.2), an exploration of commercial casein materials (5.3), the development of casein filaments (5.4) and material testing (5.5) and was carried out in various locations, including home, studio (HAG), and laboratory (UoL).

5.1 Materials And Skillsets

Wet spinning is a complex fibre production method where a polymer solution is extruded through a spinneret into a coagulation bath, forming solid filaments. This process demands precise control over various parameters, such as the composition of the polymer solution and the conditions of the coagulation bath, to ensure fibre uniformity and quality.

An early issue in manufacturing casein filaments presented itself in that the wet spinning equipment provided at UoL was unsuitable. This was for several reasons. Firstly, the historical process of using formaldehyde in the coagulation and hardening baths meant that it was unsafe to conduct this work outside of a fume hood (a negative pressure ventilated chemical workspace commonly used in chemical synthesis and experimentation), which the existing rig was too large to fit inside of. Due to its size, it would also require large volumes of coagulation solvent (tens of litres to a single trial run) to fill the baths, causing severe environmental implications regarding their disposal. Finally, the existing rig was manufactured from stainless steel, which would have been damaged by using sulphuric acid, which was again required to replicate the historical process of spinning casein.

A modular, lab-scale wet spinning rig was developed by JH (at UoL) to overcome this initial barrier, allowing for easy setup and equipment breakdown within a fume hood (referred to in this thesis as the experimental spinning rig). This modification substantially reduced the required solvent volume from tens of litres to approximately 250-500 ml. It also enabled quick and safe exploration of small-scale tests involving various casein dope formulas and spinning process parameters. Further details on the experimental spinning rig (ESR) can be found in Section 5.4.1. The development of the ESR influenced the scope of specific research activities within the PhD timeframe. During the ESR's development phase, the exploration of casein films served as an alternative to filaments. The knowledge from producing casein films was subsequently applied to filament production once the ESR was ready for testing.

Informed by the literature review, Figure 37 provides an overview of the examination of casein, illustrating the progression from material inputs to potential products in different sectors. At the top of the hierarchy are natural dyes. One of the significant environmental impacts of textile processing lies in dyeing and colouring materials. Therefore, it was crucial to source colours with minimal impact to reduce the use of harmful chemicals and the generation of toxic waste. Although casein is typically blended with other fibres, this research emphasises the concept of a mono-material archetype.

The experiments conducted in this chapter have been devised with the vision and a final range of garments in mind. Each technique explored was selected to aid the matching of material and garment speedcycle within the regenerative design framework and the compostability process at end of life. The complete list of techniques explored in this chapter, alongside the skill set required and their relevance to the creation of TCGs, are demonstrated in Table 8.

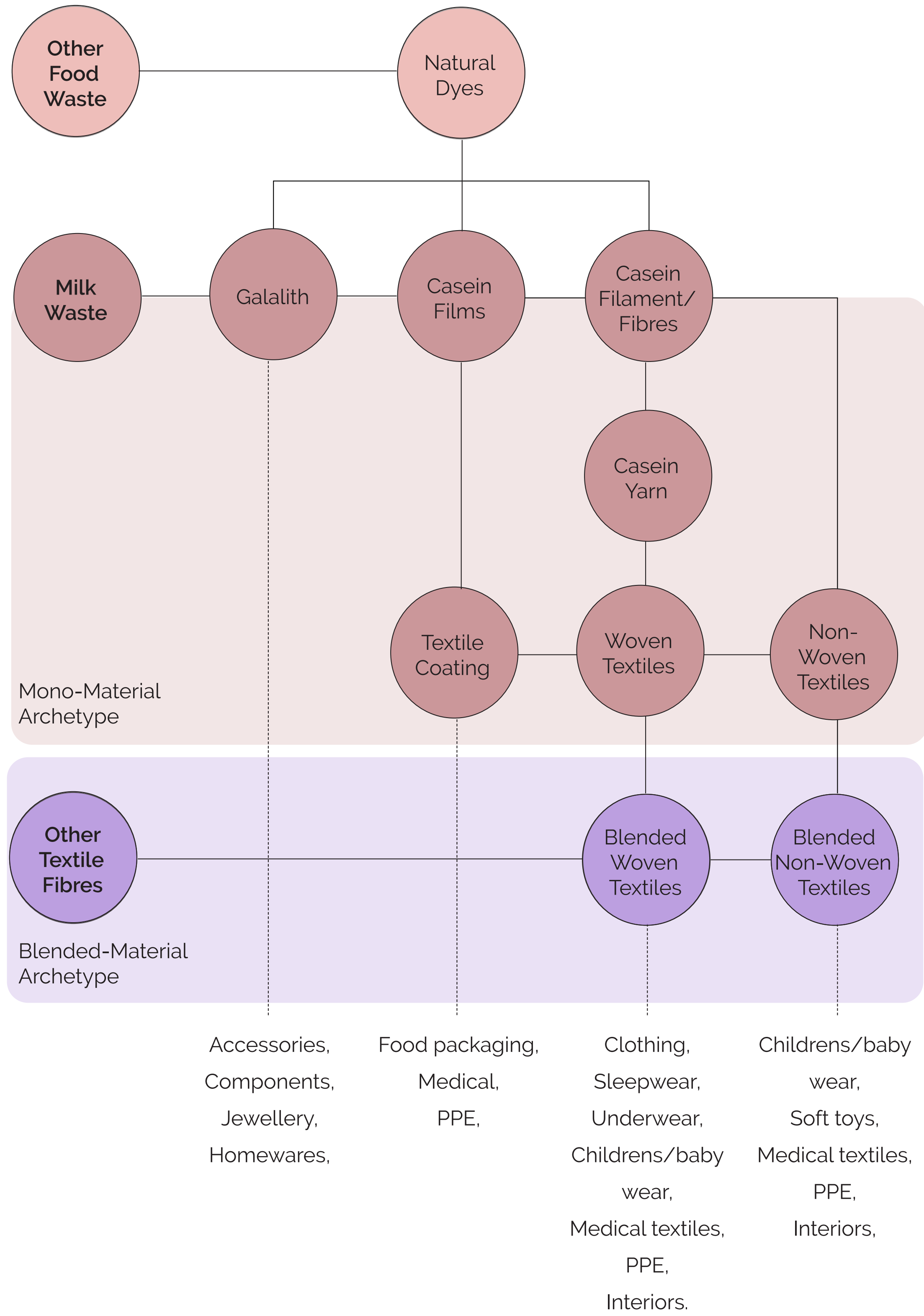


Figure 37: Structure of investigation of casein-based materials and colour.

Skill Set Used	Technique	Materials Used	Collaborators	How does this aid the matching of speedcycles within a reg framework?
Textile Design	Screen-printing	Casein fabric/ natural dyes	n/a	Chemical free print design aiding compostability
Textile Design	Yarn dyeing	Casein yarns/ natural dyes	n/a	Chemical free colouration aiding compostability
Textile Design	Weaving for disposability	Casein Yarns	HAG + MS	Speeding up of manufacturing system/ ease of breakdown at end of life
Textile design/ Chemistry	Filament colouration	Casein powder/ natural dyes	JH + MS	Speeding up of manufacturing system/ Chemical free colouration aiding compostability/Reduction in use of energy and water and production of waste
Textile Design/ Chemistry	Tensile testing	Casein yarns	JH + MS	Assessment of fibre durability and suitability
Chemistry	Thermophilic testing	Commercial casein fibres	JH + MS + EUROFINS	Confirmation of timeframe of degradation/compostability
Chemistry	Plant response Testing	Commercial casein fibres	JH + MS + EUROFINS	Conformation of improved soil quality via composting
Chemistry	Thermophilic testing	Casein filament	JH + MS + EUROFINS	Confirmation of timeframe of degradation/compostability

Table 8: Matching material technique with skill set within a regenerative design framework.

A broad range of casein-based materials are explored in this chapter, some of which have been commercially purchased and others made by participating researchers in varying locations. With the exception of woven fabrics made in collaboration with HAG at her studio, any materials created by me were done domestically. This chapter delves into a diverse array of casein-based materials, encompassing commercially purchased and researcher-made materials developed in different environments. Table 9 provides a detailed breakdown of each material, clarifying the specific attributes associated with each term used for reference.

Commercially Sourced Materials:	Composition:	Weight:		Purchased from:
Casein Fibres	100% casein	n/a		www.george-weil.com
Casein Yarns x 4	100% casein	Lace	2.7oz skeins = approx. 490yd 75g = approx. 450m	www.bellatrista.com
		Light	000ypp (24NM/4)	
		Mid	3000ypp (16NM/4)	
		Bulky	3.5oz skeins = approx. 218yd 100g = approx. 200m	
Casein Textile	100% casein fibre twill	100 gsm		www.whaleys.com
Materials Made:	Raw Ingredient/ Form of Casein	Location/Workspace		Material made by:
Galalith	Semi-skimmed milk	Domestic (Kitchen)		MS
Casein Films	Purified casein (powder)	Domestic (Kitchen)		MS
		Laboratory (UoL)		JH
Casein filament	Purified casein (powder)	Laboratory (UoL)		JH
Knitted textiles	Casein Yarns (commercial)	Domestic		MS
Woven textiles	Casein Yarns (commercial)	Studio		HAG + MS

Table 9: Materials used/referenced in this chapter:

Some of the processes used in this chapter refer to the use of certain chemicals, which are outlined in Table 10.

Chemical	Formula	Chemical	Formula
Aluminium Potassium Sulphate	$KAl(SO_4)_2$	Sodium Bicarbonate	$NaHCO_3$
Formaldehyde	CH_2O	Sodium Hydroxide	$NaOH$
Formic Acid	CH_2O_2	Sodium Sulphate	Na_2SO_4
Glycerine	$C_3H_5(OH)_3$	Sulphuric Acid	H_2SO_4
Magnesium Sulphate	$MgSO_4$		

Table 10: Chemicals used/referenced in this Chapter.

5.2 Exploration Of Casein As A Raw Material

The following experiments served as an introduction to using casein as a raw material during and immediately after the lockdown period when research facilities were unavailable or difficult to access. This section focuses on the production of galalith and casein films. Although the results were valuable, this experimentation served its purpose early on, and a decision was made (by JH and me) not to pursue this research further. As the study progressed, commercial casein materials and filaments became the primary focus.

Upon returning to the lab in October 2020, JH continued creating casein films instead of filaments due to time constraints and difficulties acquiring equipment or parts for the ESR. The film development process involved a basic formula for creating a casein dope, which could be either dried in a petri dish to form films or wet spun into fibres—the making of films allowed for the quick testing of material properties without additional solvents. Once the desired properties were achieved and the ESR became available, wet spinning of the dope could commence.

Learning Process

The learning process for this research section began with an extensive literature review. JH and I collected historical data from patents and journals, cross-referencing them to identify a common methodology. As JH replicated this methodology in the lab, regular online meetings were scheduled to discuss the trial results. JH provided explanations of the methods, formulas, and equipment used, such as petri dishes, beakers for sample measurements, and an oven for drying.

Based on this information, I procured the necessary equipment and resources to conduct similar tests at home. This included petri dishes for sample containment, measuring cylinders and beakers for accurate measurements, a syringe pipette for extracting the dope, and a magnetic stirrer for prolonged stirring. Additionally, purified casein powder, bicarbonate of soda, and glycerine were acquired as components required for making the casein dope.

Throughout the film-making process, learning, communication, and method sharing continued through video calls, discussions, note-taking, video tutorials, photography, and the exchange of reports and lab notes. These initial learnings enabled the application of new insights to the production of coloured films and sparked ideas for applying chemistry knowledge to creative practice.

5.2.1 Ex 1: Casein Extraction For Galalith

Test 1:

Aim: This initial experience working with casein aimed to understand the extraction process from regular, household milk and contextualise the material in its rawest form. The development of galalith aimed to explore the potential of using casein as a suitable material for creating components such as buttons.

Location: Kitchen
Collaborators: N/A
Tools/Materials: Milk, Vinegar, Ethanol, Oven, Strainer, Cloth.

Method: The initial formula used for this experiment was:

- 300ml of skimmed milk
- 4ml of 20% vinegar
- Ethanol
- Glycerine can be added to give flexibility.

Milk was heated to 40°c in a beaker before adding vinegar in drops using a pipette. As the milk is gently stirred, the casein will separate and clump together. Once all the casein has separated, the leftover milk is drained, and the casein is washed in warm water and ethanol, displacing the water and eliminating sugars and fats from the material. Once cleaned, the casein should have a rubbery texture. Dyes and colourants can be added to the material before moulding into shape.

Results: Once the casein had separated from the milk, it became very soft and crumbly in texture. The milk was strained through a muslin cloth to catch all the pieces, hoping it could be compressed back into one larger piece and moulded. As the material was handled, it crumbled into smaller pieces and, as it began to dry, could not be stuck back together, so they were left to air dry as they were.

The smaller pieces (roughly 1-2cm in size) took 5-6 days to dry, while larger pieces (approximately 4-5cm) took 9-10 days. Their colour and texture changed from a white, plasticine look to a yellow, plastic-like appearance, which was hard and rigid in texture.

Reflection: This initial test served as an introduction to performing lab-based experiments in a domestic setting. The method and formula worked in extracting the casein; however, moulding and shaping the material is difficult due to its flaky texture. Historically, galalith would have also been made with formaldehyde as a crosslinking agent (to create chemical links which strengthen the material), and it may be the case that an additional ingredient is needed to improve the texture and appearance of a modern-day, non-toxic alternative. There may also be a better way of moulding or creating shapes, but this would require further experimentation.

Test 2:

Aim: This second test aimed to create a more pliable material that held together well (rather than crumbling into pieces) and could be moulded into different shapes.

Location: Kitchen
Collaborators: N/A
Tools/Materials: Milk, Vinegar, Ethanol, Oven, Strainer, Cloth.

Method: After the initial unsuccessful results, the formula was tweaked slightly. As the first batch of casein had separated into small clumps, 1ml extra of vinegar (5ml in total) was added, and milk was heated to 60˚c rather than 40˚c, hoping these changes would aid the separation process. After being unable to mould the first batch, a resin casting mould kit (intended for jewellery making) was purchased. It included various shaped moulds and tools to make it easier and quicker to create shapes, with components such as buttons in mind.

Results: The results were immeditely more successful as the casein separated in one large ball that could be easily extracted from the leftover milk, washed, and strained in kitchen roll (rather than a muslin cloth to which the casein previously stuck). The leftover material was tougher and more malleable in texture with slightly more elasticity. Working with the material was still challenging to shape - mainly as it started to dry - although the resin mould kit made it much easier to work with. In using the moulds, it also became noticeable that the material shrinks significantly as it dries.

Reflection: These slight changes in the formula and method made a huge difference to the outcome of the material. Although it was still difficult to mould, it gave me a better understanding of how components could be created from casein. Regarding a finished item such as a button, the material's texture was still quite rough and would need to be either polished or filed to get a smooth finish. Again, this is a potential area where using a cross-linking agent would improve the overall finish of the material and help create a more professional finish.

Although galalith was only investigated briefly, there is a significant opportunity for further experimentation regarding the formula and shaping of the material. As in manufacturing

Figure 38: Test 1 - Extraction of casein from milk.
Figure 39: Test 2 - Extraction of casein from milk.
Figure 40: Test 2 - Moulded and dried galalith shapes.

casein-based films, glycerine could be added to test the effects on the material. As glycerine is a plasticiser, the added elasticity could make the material more flexible and easier to shape when wet. At this point, more research in this area would be needed before experimentation.

5.2.2 Ex 2: Development Of Casein Films

Aim: The broader goal of this study is to explore different manufacturing processes and formulas for casein films that can be applied to producing casein fibres. By simultaneously producing films in a domestic environment and in collaboration with JH at the lab, we could exchange knowledge and build a collaborative relationship despite being in different physical spaces. This allows for interventions at various times and stages during the development process.

Location: Kitchen
Collaborators: JH
Tools/Materials: Casein powder, ammonia, $NaHCO_3$, $C_3H_8O_3$, beaker, magnetic stirrer, measuring cylinder, pipette, oven, heater, casein fibre, casein twill, coloured inks.

Method: The experiments were conducted in batches using different formulas and drying conditions to examine the effects on the dried films. For instance, in batch 2, eight individual samples were created, with samples 2.1-2.7 containing increasing amounts of $NaHCO_3$ (ranging from 5g to 10.2g in increments of 1.2g). The remaining solution, which was viscous and foamy, was used to make sample 2.8.

Batch	F1	F2	F3	F4	F5
Components	300ml ammonia	300ml water	150ml water	150ml water	300ml water
	10g casein powder	15g casein powder	7.5g casein powder	7.5g casein powder	16g casein powder
		5 – 10.2g $NaHCO_3$	1 - 3g $NaHCO_3$	3g $NaHCO_3$	3.5g $NaHCO_3$
	3ml $C_3H_8O_3$	4ml $C_3H_8O_3$	4ml $C_3H_8O_3$	2.5 – 8ml $C_3H_8O_3$	8g $C_3H_8O_3$
Films made	0	8	8	6	11

Table 11: Casein film batch tests.

The basic formula used by JH consisted of 300ml distilled water, 16g casein, 3.5ml of 25wt% Sodium Hydroxide (NaOH) to adjust the pH, and 8g glycerine to add flexibility. Since NaOH is an irritant that can cause skin and eye damage, and considering the experiments were conducted in a domestic setting without proper means of disposal or required ventilation, Sodium Bicarbonate ($NaHCO_3$) was used as a safer alternative to adjust the pH. Different levels of $NaHCO_3$ were explored to determine the optimal ratio for producing flexible and transparent films of comparable quality to those made in the lab.

Batch	Sample	Description	Drying	Aim
F1	1.1-1.4	9ml in 90mm petri dish.	Air	To create a casein film.
F2	2.1	9ml in 90mm petri dish. (5g $NaHCO_3$)	Oven/Air	To create a range
	2.2	9ml in 90mm petri dish. (6.2g $NaHCO_3$)	Oven/Air	of casein films and
	2.3	9ml in 90mm petri dish. (7.6g $NaHCO_3$)	Oven/Air	identify how varying
	2.4	Solution poured into small silicone moulds. (7.6g $NaHCO_3$)	Air	levels of $NaHCO_3$ effects the results.
	2.5	9ml in 90mm petri dish. (8.8g $NaHCO_3$)	Oven/Air	
	2.6	4tsp of foam in 90mm petri dish. (8.8g $NaHCO_3$)	Oven/Air	To explore texture
		9ml in 90mm petri dish. (9g $NaHCO_3$)		using foam.
	2.7	9ml in 90mm petri dish. (10.2g $NaHCO_3$)	Oven/Air	
	2.8		Oven/Air	
F3	3.1	10ml in 90mm petri dish. (1g $NaHCO_3$)	Oven/Air	To create a range
	3.2	10ml in 90mm petri dish. (2g $NaHCO_3$)	Oven/Air	of casein films and
	3.3	10ml in 90mm petri dish. (3g $NaHCO_3$)	Oven/Air	identify how varying
	3.4	10ml + 100% casein twill in 90mm petri dish. (3g $NaHCO_3$)	Oven/Air	levels of $NaHCO_3$ effects the results.
	3.5	20ml + 100% casein twill x2 in 90mm petri dish. (3g $NaHCO_3$)	Oven/Air	
	3.6	12ml in 90mm petri dish. (3g $NaHCO_3$)	Heater	
	3.7	14ml in 90mm petri dish. (3g $NaHCO_3$)	Heater	
	3.8	25ml in 100mm silicone mould. (3g $NaHCO_3$)	Heater	
F4	4.1	10ml in 90mm petri dish. (2.5g $C_3H_8O_3$)	Oven/Air	To identify how
	4.2	20ml in 90mm petri dish. (2.5g $C_3H_8O_3$)	Oven/Air	Glycerine and larger
	4.3	10ml + 100% Casein twill in 90mm petri dish. (2.5g $C_3H_8O_3$)	Oven/Air	measurements of solution effects
	4.4	10ml in 90mm petri dish. (5g $C_3H_8O_3$)	Oven/Air	the results and to
	4.5	20ml in 90mm petri dish. (5g $C_3H_8O_3$)	Oven/Air	achieve a clearer,
	4.6	20ml in 90mm petri dish. (8g $C_3H_8O_3$)	Oven/Air	stronger film.
F5	5.1	10ml in 90mm petri dish.	Heater	To improve clarity
	5.2	10ml in 90mm petri dish.	Heater	and strength.
	5.3	10ml in 90mm petri dish.	Heater	
	5.4	10ml in 90mm petri dish.	Oven/Air	To create a range
	5.5	10ml in 90mm petri dish.	Oven/Air	of coloured or
	5.6	10ml in 90mm petri dish.	Oven/Air	patterned samples
	5.7	4tsp of foam in 90mm petri dish	Oven/Air	using inks.
	5.8	10ml with casein fibre in 90mm petri dish	Oven/Air	
	5.9	10ml in 90mm petri dish. Drops of ink not mixed.	Heater	To explore texture
	5.10	10ml in 90mm petri dish. Drops of ink lightly mixed.	Heater	using foam.
	5.11	10ml in 90mm petri dish. Drops of ink mixed.	Heater	

Table 12: Casein film batch description and aim..

Results: Sodium Bicarbonate: During the waiting period for equipment such as measuring scales to arrive, $NaHCO_3$ was measured using a teaspoon. Unfortunately, these measurements were excessively large, leading to cloudy and gelatinous samples. Subsequent discussions with JH prompted the use of significantly smaller starting measurements. A reduced quantity of 1-3g of $NaHCO_3$ yielded improved results, with the films becoming more transparent and able to peel from the dish without tearing. The texture remained sticky in texture and resembled a thin cling film, showing slight variation across the samples.

Following further discussions and live video tutorials with JH in the lab, batch 5 emerged as the most successful formulation and methodology for future use. The adjustments made included using a standardised measurement of 3.5g $NaHCO_3$ and increasing the amount of formula per sample. The new samples exhibited enhanced transparency, and strength, and eliminated stickiness. Increasing the solution volume to 10ml provided slightly improved stability. Some samples still showed frosting in certain areas, which could be attributed to external factors like trapped air or drying conditions. Overall, the texture of these samples resembled clear PVC material.

Glycerine: Batch 4, which involved varying levels of glycerine, yielded inconclusive and disappointing results. All six samples were dried uninterrupted for eight hours in the oven and then air-dried for two more days. Initially, the samples appeared dark yellow and exhibited uneven texture with areas of crystallisation. Once dried, the samples adhered to the bottom of the dishes and tore easily, making them impossible to remove. The exact cause of this batch's failure is uncertain but likely related to the drying conditions. Domestic ovens are unpredictable, as the precise temperature cannot be determined. Despite setting it to 50°C, the actual temperature might have been higher, leading to dehydration of the material components.

Mixed Media Samples: Samples coated with a layer of casein twill fabric exhibited a more yellowish colour, particularly with higher levels of $NaHCO_3$ and larger solution measurements. The mixed media materials dried stronger yet remained flexible. Higher solution volumes over the fabric resulted in increased brittleness and curling at the edges. Adding coloured inks to the solution in the final stage provided insights into creating patterns or block dye materials. The water-soluble inks with a shellac medium yielded bright and vivid finishes. Colour could be uniformly mixed or dropped using a pipette to achieve desired colour or multi-coloured effects.

Conditions: Due to frequent relocation, the overall impact of drying conditions on the samples is difficult to ascertain. As the experiments were conducted domestically, samples were sometimes placed on a radiator or moved between heat sources for drying, depending on the time of day. This variability made it impossible to evaluate the specific effect of different drying methods on the final results.

Reflection: Several factors influenced the successes and failures of this ongoing experiment, many of which stemmed from working in a non-specialized environment. Delays in equipment delivery hindered precise component measurements until midway through batch three. Balancing workspace and home life also affected the results. In contrast to a controlled lab environment where film samples are left in a conditioning unit at a consistent temperature, using a domestic oven requires frequent removal and potential disturbance of the samples. Alternatively, relying solely on room temperature air drying would take up to a week and necessitate a safe space to avoid accidental disruptions.

Overall, these experiments served as a valuable tacit learning exercise in establishing a methodology for working with an unfamiliar material within a home or studio environment. The collaborative nature of this project became evident through conversations, tutorials, and photography, enabling effective research communication and bridging the knowledge gap between disciplines.

5.2.3 Ex 3: Development Of Coloured Casein Films

Aim: This study investigates the impact of incorporating natural food waste dyes on the production and quality of casein films. Since $NaHCO_3$ is used in both the development of casein films and can be used in natural dyes as a mordant, the study explores the combined effect of these processes.

Location: Kitchen
Collaborators: JH
Tools/Materials: Casein powder, avocado dye, blueberry dye, $NaHCO_3$ $C_3H_8O_3$ beaker, magnetic stirrer, measuring cylinder, pipette, oven, heater, casein twill.

Method: The initial series of tests involved batch 6, which used the leftover casein formula from batch 5 of the previous film experiments. The solution was divided into four dishes, and a small amount of avocado dye was added to each sample using a pipette. Batches 7 and 8 were prepared with new solutions where the water content was entirely replaced with dye.

Avocado and blueberry dyes used in this experiment were prepared following the methods outlined in Ex 4 (p128). 600ml of each dye was prepared by boiling the dyestuffs in water for 30 minutes, steeping for 2 hours, and re-boiling for an additional hour. This process prevents burning and ensures high-quality colour extraction. After straining through muslin cloth, each dye was left to develop for 24 hours, with pH measurements taken before and after to assess colour maturation. Both dyes were selected due to their intense colours observed during Ex 4.

The effects of an alkali and an acid dye casein solution were also compared.

Batch	Sample	Description	pH (Dye)	PH (Solution)
F6	6.1	20ml in 90mm petri dish. 10 drops of Avocado dye added.	8.58 (Alkali)	8.6 (before dye)
	6.2	15ml in 90mm petri dish. 10 drops of Avocado dye added.		
	6.3	10ml in 90mm petri dish. 10 drops of Avocado dye added.		
	6.4	Foam in 120mm silicone mould. 10 drops of Avocado dye added.		
F7	7.1	20ml in 90mm petri dish. 100% avocado dye water replacement.	8.58 (Alkali)	8.91 (dye included)
	7.2	15ml in 90mm petri dish. 100% avocado dye water replacement.		
	7.3	10ml in 90mm petri dish. 100% avocado dye water replacement.		
	7.4	10ml + 100% casein twill in 90mm petri dish. 100% avocado dye water replacement.		
	7.5	Foam in 90mm petri dish. 100% avocado dye water replacement.		
F8	8.1	20ml in 90mm petri dish. 100% blueberry dye water replacement.	4.4 (Acid)	8.2 (dye included)
	8.2	15ml in 90mm petri dish. 100% blueberry dye water replacement.		
	8.3	10ml in 90mm petri dish. 100% blueberry dye water replacement.		
	8.4	Foam in 90mm petri dish. 100% blueberry dye water replacement.		

Table 13: Coloured casein film batch description and results.

Results: Batch F6: The initial test produced a subtle peachy colour with a few drops of dye without significantly affecting the quality. However, the colour appeared uneven and could have benefited from further mixing. Sample 6.4 did not dry as expected, possibly due to dehydration from oven drying. The texture and colour of 6.4 was also uneven, which could be attributed to oven drying, sample disturbance, or using a flexible silicone mould instead of a rigid petri dish.

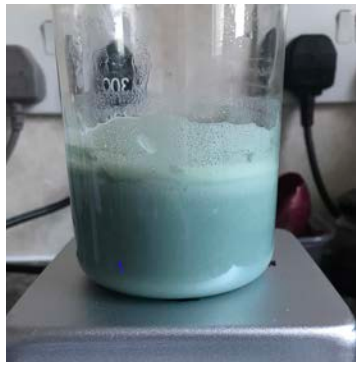
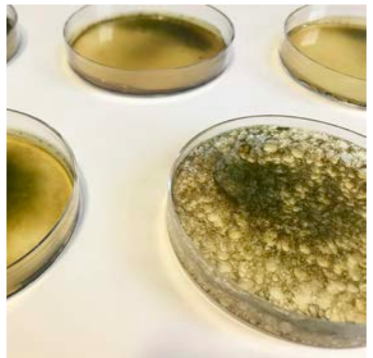
Batch F7: Batch 7 exhibited a darker colour. Following the established film-making process, the dye was mixed directly with casein powder for 2 hours before adding $NaHCO_3$ and glycerol, resulting in a more even colour. As the samples dried, they transitioned from a lighter pink to a deep red. The overall quality was similar to previous batches, but the texture was slightly stickier, leading to minor tears around the edges upon extraction. Sample 7.5 showed an interesting effect when using foam, creating a flatter and glossier bubbled pattern within the material.

Batch F8: This batch yielded intriguing results due to the initial pH of the blueberry dye. Initially, the dye had a dark purple colour, which turned into a light pastel shade of purple when mixed with casein powder. Adding $NaHCO_3$ resulted in a second, visible colour change to a bright blue/green due to increased pH. Despite the light colour of the solution, the dried films exhibited a dark green shade. After a few weeks, the films changed to dark yellow. While this may pose challenges in achieving specific colours in the films due to the involvement of $NaHCO_3$, it presents opportunities for further experimentation and analysis.







Figures from top right to left:
Figure 41: Batch F6, Sample 6.1.
Figure 42: Batch F6, Sample 6.4.
Figure 43: Batch F7, Sample 7.1.
Figure 44: Batch F7, Sample 7.5.
Figure 45: Batch F8, Sample 8.1.
Figure 46: Batch F8, Sample 8.4.
Figure 47: Initial colour of dye before adding $NaHCO_3$.
Figure 48: Colour after adding $NaHCO_3$.
Figure 49: Colour of films once initially dried. CO_3.

Batch	Sample	Description	pH (dye)	pH (solution)
F6	6.1	20ml in 90mm petri dish. 10 drops of Avocado dye added.	8.58 (Alkali)	8.6 (before dye)
	6.2	15ml in 90mm petri dish. 10 drops of Avocado dye added.		
	6.3	10ml in 90mm petri dish. 10 drops of Avocado dye added.		
	6.4	Foam in 120mm silicone mould. 10 drops of Avocado dye added.		
F7	7.1	20ml in 90mm petri dish. 100% avocado dye water replacement.	8.58 (Alkali)	8.91 (dye included)
	7.2	15ml in 90mm petri dish. 100% avocado dye water replacement.		
	7.3	10ml in 90mm petri dish. 100% avocado dye water replacement.		
	7.4	10ml + 100% casein twill in 90mm petri dish. 100% avocado dye water replacement.		
	7.5	Foam in 90mm petri dish. 100% avocado dye water replacement.		
F8	8.1	20ml in 90mm petri dish. 100% blueberry dye water replacement.	4.4 (Acid)	8.2 (dye included)
	8.2	15ml in 90mm petri dish. 100% blueberry dye water replacement.		
	8.3	10ml in 90mm petri dish. 100% blueberry dye water replacement.		
	8.4	Foam in 90mm petri dish. 100% blueberry dye water replacement.		

Table 14: Batch description for coloured casein films.

Reflection: This phase of experimentation was highly insightful as it marked the initial stage of combining results through knowledge integration and transdisciplinary practice. Exploring the interaction between pH in casein-based materials and natural dyes derived from food waste opened a new avenue for sustainable manufacturing of casein-based textiles. From a life cycle assessment (LCA) perspective, adding colour to the casein formula at the pre-fibre stage could eliminate the need for dyeing during textile processing, reducing water and energy consumption, and eliminating additional fixing agents.

Furthermore, from a chemical standpoint, this study initiated a discussion between JH and me regarding the potential of natural colouring agents to enhance the final material or contribute to other properties, potentially as alternatives to cross-linking agents. It also raises the possibility of utilising natural tannins such as avocado as cross-linking agents, enabling comparisons to other biomaterial industries (Moghaddam, Biazar et al., 2023; Picchio, Linck et al., 2018).

5.2.4 Applying The Outcomes Of Knowledge Integration: Ex 1-3

The initial extraction and moulding of galalith from casein provided a successful introduction to working with casein as a raw material. This process allowed for an initial understanding of casein's material properties and behaviours, laying the foundation for applying this knowledge to the extrusion of textile fibres.

During this stage, JH focused on film development in the laboratory while maintaining ongoing discussions about methods and results. This collaborative approach facilitated communication, connecting scientific and creative thinking processes and decision-making.

These early experiments highlighted the importance of precision regarding components and formulas. Even minor changes, such as adding an extra 1ml of vinegar during casein extraction, significantly impacted the extraction process and the final appearance of the galalith material. Although seemingly simple, these lessons were considered throughout subsequent experiments. In contrast, creative practices often rely on subjective measurements, whereas scientific rigour requires careful scrutiny of components.

The development of casein films provided valuable insights into the chemical composition and potential properties of casein filaments and the associated production methods used in the laboratory. JH's work on casein films allowed for an assessment of the potential challenges when transitioning to filament production, including thermal analysis, chemical analysis, thickness testing, and tensile properties. The impact of different drying methods and alternative cross-linking agents, such as formaldehyde, citric acid, and furfural, were also explored by JH at UoL.

Fortnightly meetings between JH and I facilitated discussions surrounding test results. By assessing my own films visually and by touch, I could reflect on alternative approaches and understand the impact of various conditions. Notably, the issue of drying conditions emerged as a significant challenge, as finding suitable physical space and consistent heat sources proved difficult. Understanding the drying process and its influence on results became clearer through discussions with JH.

Conversations with JH also inspired incorporating natural dyes into the initial formula to colour the material and influence its properties in one stage. The hypothesis was that natural dyes containing tanning agents could strengthen the material. These early tests combining casein dope with natural dyes provided insight into translating this process to filament production.

This theory was expanded upon during a lab visit to UoL, and a method for dyeing casein filaments during the wet spinning processes with blackcurrant powder provided by Keracol was developed (5.4.3). Additional tests were also conducted to assess the effect of natural dyes containing tannins on the durability of casein yarns (5.5.1).

5.3 Exploration Of Commercial Casein Materials

This section of the thesis documents an exploration of commercially available casein materials, including casein twill, casein fibres and various weights of casein yarns. Commercial casein materials were utilised at this point as developments to the ESR were still underway, and not enough lab-produced filament could be made for this type of experimentation.

The following experiments aimed to expand the techniques available for the design of regenerative garments created from casein. Beginning with an exploration of colour and print, a range of natural dyes and screen-printing inks were developed and tested on various casein-based materials, including casein twill fabric, casein yarns and casein fibres. The decision was made to work exclusively with food waste as a source or colour, aligning with the research's regenerative principles and collaboration with other industries to reduce waste further.

The experiments then explore textile construction techniques through the development of knitted and woven samples using casein yarns. The exploration of casein yarn served as a bridge between raw materials and garment perspectives and allowed a more comprehensive understanding of material properties and behaviours.

Learning Process

Online research was conducted into natural dyes explicitly created from food waste, and the book 'Botanical Colour at your fingertips' (Desnos, 2016) was used as a practical guide throughout this experimentation. I also attended a one-day natural dye workshop (Stemwell Workshop: Introduction to natural dyeing, Peckham) as a part of the learning process. Although this workshop included examples of plant and food waste dyes, it was utilised as an opportunity to compare the results of dyes on casein fabric to other textile materials such as cotton and silk, as well as to pick up additional tips and tricks in terms of mordanting and variations of the process.

Working with Keracol was essential to taking my tacit knowledge of dyes out of a 'craft-based' space and into a laboratory environment. Knowledge exchange between Dr Alenka Tidder (AT) and I became the focal point of this body of practice. This was a unique opportunity, not only for me to learn from AT about the extraction of anthocyanins and the lab-based process of creating textile dyes but also for me to share my experiences of working with casein and other anthocyanin dyes (red onion skins) and to combine our collective knowledge to solve problems in the same physical space.

Collaborating with HAG was also necessary for the learning process. Weaving requires a set of complex equipment as well as time and knowledge to initially set up the loom, which was not feasible for me to learn within the context of this study. After an initial discussion with HAG, we decided the best way to proceed was for me to go to her studio and view the weaving process from start to end. HAG demonstrated this process whilst I observed and took notes and photographs. I would then develop a range of small-scale samples to understand the initial challenges of weaving with casein before moving to the design stage. After knitting with casein, specific hypotheses had been made about working with the yarns, so this would serve as an exciting opportunity to test them in a different construction method using other equipment.

Initial Assessment Of Commercial Casein Yarns

Casein fibres were purchased for an initial assessment of material properties. Commercially sourced fibres were the first casein-based material I could see and touch in person. As a textile designer with a background in surface design and colour, seeing and feeling material in this raw state was unfamiliar to me. I had never spun fibres into yarn before and did not have access to any spinning equipment or facilities. Nevertheless, simply handling the fibres allowed me to recognise specific textile properties.

The fibres were a natural cream colour and had a glossy sheen. They were incredibly soft and lightweight, and as I pulled the fibres apart with my hand, I noticed they were short in length (this is due to the staple length the fibres are cut to, making them ready for spinning into yarn) and shed easily. This initial assessment of existing casein fibres allowed me to build a profile of what to expect going forward in terms of the ease or difficulty in working with other casein materials.

5.3.1 Ex 4: Colour From Food Waste: Commercial Fabric

Aim: The primary objective of this experiment was to generate a diverse range of coloured dyes from food waste and assess the fabric's absorption capacity for each dyestuff. The investigation involved using natural and non-toxic mordanting techniques to identify enhancements in colour quality and colour variations.

Location: Kitchen
Collaborators: N/A
Tools/Materials: Aluminium pan, hob, measuring jug, weighing scales, avocado dye, blueberry dye, black bean dye, spinach dye, $NaHCO_3$, vinegar, soy milk, washing machine, PH meter, strainer, muslin cloth.

Method: Mordanting: A mordant serves to strengthen the bond between dye and fibre. Protein fibres such as wool or silk typically possess inherently higher absorbency than cellulose fibres and are less reliant on mordants. Some natural dyes, like avocado stones and pomegranate skins, are classified as substantive dyes due to their tannin content, which acts as a natural mordant, resulting in darker and more colourfast shades. Conversely, cellulose fibres often benefit from treatment with soy milk as a natural mordant. The soy protein adheres to the fibre, modifying its properties to behave more like a protein fibre, thus producing stronger and more durable colours.

Although casein is a protein fibre and should inherently possess colourfast properties, each dye was tested on mordanted and non-mordanted swatches of 100% casein fibre twill to assess its natural properties. Approximately 50g of fabric (equivalent to roughly ¼ of a metre) was washed at 30°C and dried until damp. A mixture of 125ml of soy milk and 625ml of water was prepared, and the damp fabric was added and left to soak for 12 hours. The coated fabric was spun in a washing machine to remove excess liquid before air-drying. This process was repeated one week later to provide a double coating. The dry, mordanted fabric was stored in a cupboard for an additional week before dyeing to ensure complete absorption and bonding of the protein with the material.

Certain metals can also serve as mordants. Using an aluminium pan as a reactive dye pot, the properties of alum can be extracted safely without using fine powders, which can be toxic in large quantities. The longer the dye is in contact with the aluminium pot, the greater the influence of the metal. Aluminium pots help intensify colours and yield additional shades depending on the dyestuff and duration. Conversely, iron and copper pots are used to darken colours. An aluminium pot was utilised for this experiment to achieve more vibrant dyes. Each dye was left in the pot for 24 hours to facilitate colour development before usage.

pH: The pH level also plays a vital role in determining the colour of a dye bath. Certain dyes are sensitive to changes in pH and can exhibit significant colour shifts based on acidity. An acid dye has a pH value below seven and can be achieved by adding vinegar or lemon juice, while an alkali dye has a pH value above seven and can be created by adding $NaHCO_3$.

In addition to testing each dye on mordanted and non-mordanted fabric swatches, pH levels were also assessed by dividing each dye into three containers: one with the dye alone, one with the dye and vinegar, and one with the dye and $NaHCO_3$ (resulting in six fabric samples per dye). The pH of each dye was measured using a digital pH meter.

Dye Extraction: Each dye used resulted from an active decision to utilise only my own household food waste. Initial experimentation involved creating small batches of dye (600ml to 1 litre). Potential collaborations with local food stores and cafes/restaurants could be pursued for larger dye batches to obtain larger quantities of waste.

Dye	Avocado	Blueberry	Black Bean	Spinach
Components	82g dried avocado (skins + 2 stones)	150g blueberries	235g black beans	100g spinach
	1 litre water	600ml water	1 litre water	1 litre water
pH	8.58	4.4	6.97	7.8
pH + 24 hours	7.4	3.9	6.6	6.5
pH + vinegar	4.81	3.84	5.35	4.15
pH + $NaHCO_3$	8.08	7.99	8.09	8.03

Table 15: Experiments conducted in terms of dyestuff and mordanting.

To maximise surface area and extract the most colour, larger food pieces, such as avocado skins, were initially dried and cut into smaller pieces. Water was brought to a boil in a pot, and the dyestuff was added and mashed to release the pigment. For each dye, the water and dyestuff were boiled for 30 minutes, then the heat was turned off, and the mixture was left to steep for 2 hours. The dye was then re-boiled and left for an additional hour. This staged process ensures the dyestuff does not burn while still extracting a high-quality colour. The dye was strained through a muslin cloth and poured back into the aluminium pan with the lid on, allowing it to develop for 24 hours. The pH of each dye was measured before and after the 24-hour development period to compare how each colour matured in the pot.

Once the dye was ready, it was divided equally among three containers. Ten drops of 20% vinegar were added to one container, and 2.5g of $NaHCO_3$ was added to another container. A swatch of mordanted and non-mordanted 100% casein fibre twill (approximately 5x5cm) was placed in each container and left for 24 hours. Afterwards, all swatches were washed in water to remove excess dye and left to air dry.

Results:
Avocado Dye: The avocado dye produced a remarkably vibrant colour, one of the strongest among the dyes tested. Interestingly, there was little discernible difference in colour intensity between the mordanted and non-mordanted swatches, although the mordanted swatches appeared slightly darker. Additionally, variations in pH did not significantly affect the dyes colour. This may be due to avocado dye's strong pigmentation, which remains consistent regardless of mordants or pH variations. This indicates the dyes' robust binding capabilities and suggests resilience to acidic or alkaline conditions.

Blueberry Dye: The blueberry dye also yielded a rich and deep colour. Like the avocado dye, soy mordant did not noticeably impact colour strength. However, the non-mordanted swatches exhibited patchier and less evenly distributed colours than the mordanted ones. Altering the pH of the dye using $NaHCO_3$ shifted the colour from a blue/purple hue to a grey/greenish shade.

Black Bean Dye: Mordanting substantially influenced the black bean dye. The mordanted swatches displayed a soft pink colour, while the non-mordanted swatches exhibited minimal colouration. The addition of $NaHCO_3$ or vinegar had minimal effect on the overall colour outcome.

Spinach Dye: Despite the initial deep green colour of the spinach dyebath, the resulting colours on the fabric were more neutral and beiger in tone. The vinegar-mordanted swatch developed into a pleasant, pale shade of yellow, while the other swatches had an earthier undertone.

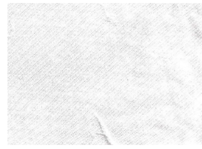
Dye	Description	Colour	Colour + Vinegar	Colour + $NaHCO_3$
Avocado	Mordanted 100% casein twill			
	Non-mordanted 100% casein twill			
Blueberry	Mordanted 100% casein twill			
	Non-mordanted 100% casein twill			
Black Bean	Mordanted 100% casein twill			
	Non-mordanted 100% casein twill			
Spinach	Mordanted 100% casein twill			
	Non-mordanted 100% casein twill			

Table 16: Results of dye tests.

Reflection: The assortment of results obtained from these dye experiments was both surprising and informative. While stronger colours were expected from the black bean and spinach dyes, it is important to acknowledge that this was the first attempt at utilising food waste for dye extraction. It is possible that specific components of the dyestuffs require more time to develop fully or that the fabric may benefit from longer soaking periods. The colour assessment was conducted using the naked eye, a common practice in textile design. However, some subtle colour differences made it challenging to determine if one approach was more successful than the other. Future experimentation involving additional food waste sources and alternative dye extraction methods would undoubtedly contribute valuable insights to this research.

5.3.2 Ex 5: Colour From Food Waste: Workshop (Various)

Aim: The primary objective of attending this workshop was to conduct a comparative study on the performance of various natural dyes on casein fabric compared to other materials. In addition to expanding my knowledge through personal experience and literature, the workshop provided an opportunity to learn about the natural dyeing process from an expert in the field.

Location: Studio
Collaborators: Stemwell Workshop: Introduction to natural dyeing
Tools/Materials: Large dye pan, hob, water jug, measuring scales, dyes (yellow onion skins, red onion skins, walnut husk, turmeric, weld, logwood, avocado skins, cutch, red Cabbage, bay leaves, madder, and hibiscus), iron, acid, alkali, casein twill, silk, wool, cotton, linen, and hemp.

Method: This one-day workshop involved the exploration of twelve different natural dyes. Each participant was assigned 1-2 dyes to work with, following a set of provided instructions. Strips of each fabric were cut and distributed among the participants. Additionally, I brought my own casein fabric swatches and requested that one be included in each dye. The effects of three mordants—Iron, Acid, and Alkali—were also tested for each fabric sample. All fabrics used in the workshop had been pre-scoured.

In my case, I prepared red cabbage dye and red onion skin dye. Approximately two litres of water were used for each dye pan. A ratio of 50% of the fabric weight was used to measure the necessary amount of dyestuff. For example, if 100g of fabric was used, 50g of onion skins should be used. The material to be dyed was soaked in a bowl of water to open up the fibres and facilitate better dye absorption. Each dye was simmered for one hour and then strained. Subsequently, a strip of each pre-soaked fabric (including casein) was added to the respective dye bath and left to soak over low heat for 30-40 minutes.

Figure 50: Colour extraction: red cabbage

Figure 51: Colour extraction: red onion

So far, this methodology was similar to my own approach, which involved a loose measurement of components and ratios of dyestuff to water. However, the main difference emerged after the dyeing process. While I had previously divided my dyes and added modifiers such as vinegar and $NaHCO_3$ directly to the dye bath before introducing the fabric, in this workshop, the material was pre-dyed, cut into smaller swatches, and then each swatch was added to a separate pot—one with an acidic modifier (vinegar and water), one with an alkaline modifier (Soda ash), and one with iron—to modify the original colour. Typically, the fabric was left in each modifier for 20 minutes.

Results: The outcomes of this experiment were varied and, in certain aspects, unexpected. Since casein is a protein-based fibre, it was anticipated to exhibit similar reactions to silk. However, the results presented in Table 17 indicate that casein generally produced more subdued colours compared to silk and hemp, which yielded richer and darker shades. Additionally, it is evident that substantive dyes, such as avocado, turmeric, and walnut, consistently generated the most reliable results across all materials.

Figure 52: Dyed fabric samples laid out on table.

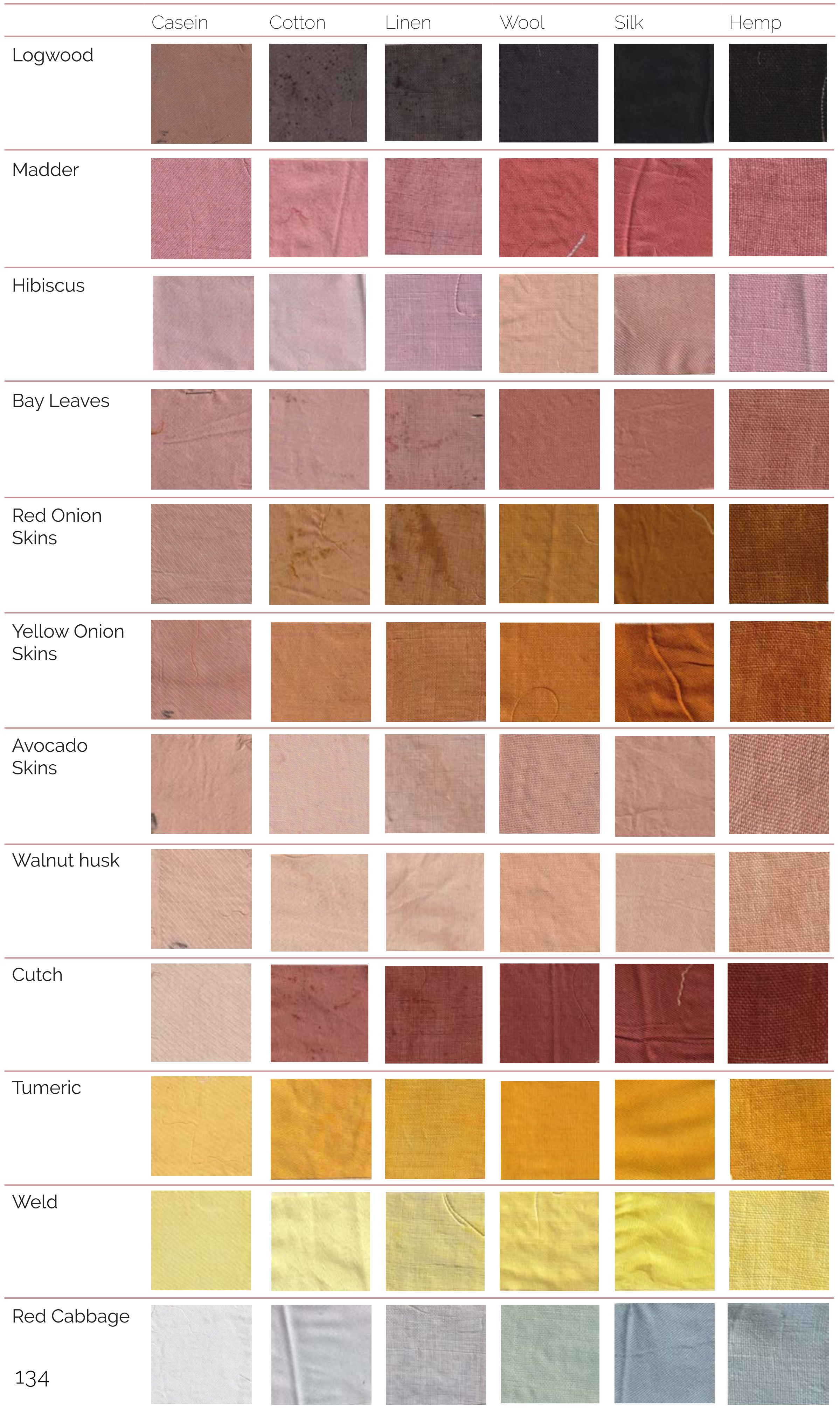


Table 17: Results, 'Colour and dye: workshop'.

Reflection: The findings from this workshop align with the initial home dyeing experiments discussed in Section 4.3.1, where the observed colours were less vibrant than anticipated. Instead, the hues obtained ranged from delicate, muted pinks, purples, and beiges to yellows. It is important to note that this should not be regarded as an unsuccessful experiment but rather as an indication that further investigations into mordanting are necessary. Moreover, the store-bought casein fabric used in this study could be affected by certain chemicals, such as formaldehyde, which might have been employed during the fabrics manufacturing process, potentially interfering with the dyes performance.

To further understand these results, additional tests have been conducted on alternative casein materials, such as yarns, which may have undergone different processing techniques. Section 5.3.3 details a comparative study specifically on red onion skins (ROS) employing various mordants and casein-based materials to explore this hypothesis.

5.3.3 Ex 6: Colour From Food Waste: (Red Onion Skins)

Aim: This research section focuses on utilising a specific source of food waste and exploring its stabilisation for fabric and yarn production. The selection of ROS was based on their containment of anthocyanins (Deveoglu 2022) and low pH, posing a challenge for achieving colour stability (Enaru et al., 2021). The experiment aimed to assess the wash fastness of the dye and compare the dye uptake between casein yarns and the fabric, which had been the primary material tested thus far.

Location: Kitchen
Collaborators: N/A
Tools/Materials: Aluminium pan, hob, measuring jug, weighing scales, ROS, $NaHCO_3$, vinegar, casein twill, PH meter, strainer, muslin cloth.

Method: The established dyeing process from Section 5.3.1 was followed to investigate the stability of the dye on casein fabric and yarn. A total of 25g of ROS were soaked in 1 litre of water in an aluminium pan overnight. After straining the dye, the pH was measured at 5.6 (acidic). Several tests were conducted using this batch of dye:

Onion Test 1: Basic dye Test of casein fabric in wash bath, washed in tap water.
Onion Test 2: Repeat of Test 1, leaving fabric to dry before rinsing.
Onion Test 3: Repeat of Onion Test 1, not washed.
Onion Test 4: Basic dye test of casein yarns, washed in tap water.
Onion Test 5: Testing of various pH.
Onion Test 6: Altering pH as a method of creating a pattern.

Results: Onion Test 1: A strip of casein fabric was immersed in the dye bath for 24 hours, resulting in a deep reddish-brown colour. However, upon rinsing the fabric under tap water, the colour quickly faded to a golden yellow. This colour change upon rinsing in tap water had not been observed before.

Onion Test 2: Test 1 was repeated to observe the change in colour upon rinsing. It was hoped that by leaving the fabric to dry before rinsing, the dye might penetrate the fibres more deeply, helping to stabilise the colour. Upon rinsing, however, the colour changed to a golden yellow again.

Onion Test 3: Another piece of fabric was placed in the dye bath for 24 hours but was not rinsed, allowing for a comparison of colour. The unwashed material retained its deeper, reddish-brown colour once dried.

Onion Test 4: Several 5-inch strands of yarn were knotted together and immersed in the dye bath for 3 hours. The yarn retained its colour much better than the fabric upon rinsing, closely resembling the unwashed colour of test 3.

Based on the results of these initial tests, it became evident that the casein fabric exhibited a colour stability issue. In contrast, casein yarns and fibres retained their colour better and demonstrated greater stability. The pH of the tap water used was measured at 7.7 (alkaline), significantly higher than the pH of the acidic onion dye (5.6).

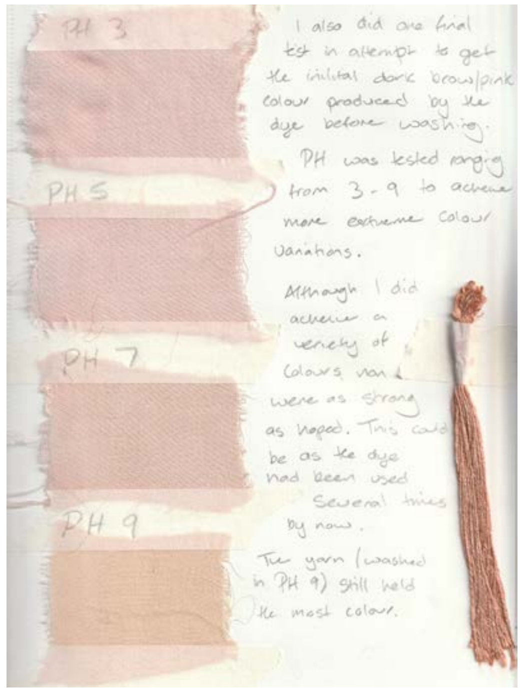
From here, it was hypothesised that dyes with a lower acidic pH might be less stable than higher pH dyes like avocado dyes and are, therefore, more susceptible to change when in contact with something of a higher pH. To explore this further, additional tests were conducted by washing swatches in varying pH solutions to observe colour changes.

Onion Test 5: A fabric sample was dyed and divided into four swatches for further experimentation. Each swatch was washed in water with pH adjustments using vinegar (lower pH) or baking soda (higher pH) to achieve pH levels ranging from 3 to 9. Notably, the lowest pH achievable using vinegar was 3, while formic acid was necessary to reach pH levels between 1 and 2. Additionally, one yarn swatch was washed at pH 9 (Figure 53).

The swatches washed at pH 3 and 5 exhibited a pale pink colour reminiscent of avocado dye. On the other hand, swatches washed at pH 7 and 9 displayed similar yellow tones. Three larger fabric pieces were also dyed and reserved for future screen-printing applications.

This test highlighted the substantial influence of the wash water's pH on fabric colour, in contrast to avocado dye, which typically has a pH of 7 and contains tannins that aid in dye stabilisation. These results suggest that the red onion dye might not penetrate the fabric effectively, leading to surface dye susceptibility when exposed to contrasting pH conditions. Figure 55 visually represents the complete range of materials dyed in the same dye bath and washed at varying pH levels.

Onion Test 6: This understanding of colour change allowed for basic experimentation with print techniques. Figure 54 demonstrates the use of vinegar drops to create a polka-dot effect. Pink spots were formed by dropping vinegar onto prewashed (pH 7) onion-dyed fabric at desired locations. As the vinegar absorbed into the fabric, a green ring appeared around the spot, adding a third colour to the fabric.



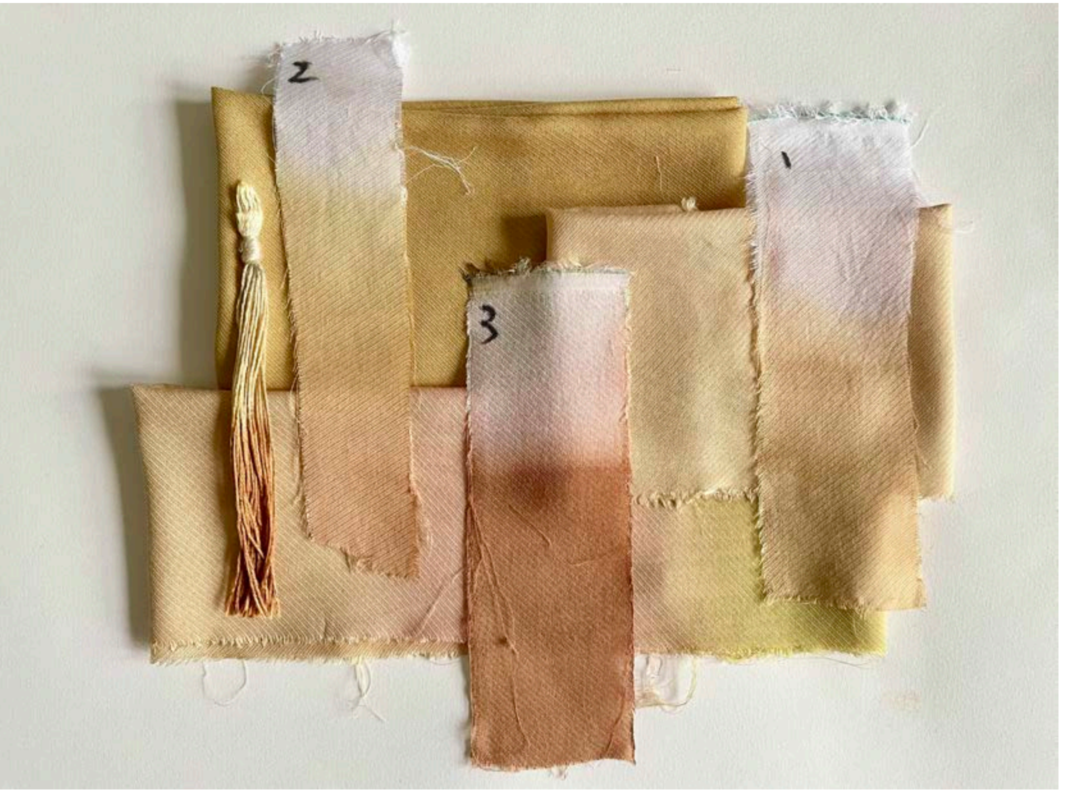


Figure 53: Onion test 4 - page from sketchbook.
Figure 54: Onion test 6 - polka dot pattern created with vingar.
Figure 55: Demonstrates the range of colours created from tests 1-4.

Reflection: The results of the experiments conducted so far have provided valuable insights into the colour stability of ROS dye on casein fabric and yarn. The findings indicate that the casein fabric is more prone to colour changes upon rinsing, while the casein yarns demonstrate better colour retention. This result suggests that the dye penetration into the fabric may be insufficient, leading to surface dye susceptibility when exposed to contrasting pH conditions.

One interesting observation is the influence of wash (tap) water pH on the fabric's colour. Comparing the red onion dye to other food waste dyes, such as avocado dye, which has a higher pH and contains natural tannins aiding dye fixation, we can infer that the red onion dye lacks effective penetration and stabilisation mechanisms. This opens up opportunities for further investigation into the dyeing process and understanding the interactions between dye and casein fabric at different pH levels and through alternative dyeing methods.

Future experimentation can focus on optimising the dyeing process to enhance colour stability on casein fabric. For instance, modifying the dye bath composition by incorporating mordants or additives may improve dye absorption and fixation. Additionally, exploring alternative pH adjustment methods or investigating the effects of different pH ranges on colour stability can provide further insights into the underlying mechanisms.

It would be beneficial to explore the potential of other natural dyes with varying pH levels to compare their colour stability on casein fabric. This comparative study can help identify dyes that exhibit better compatibility, paving the way for developing long-lasting dyeing techniques.

Furthermore, applying the red onion dye on larger fabric pieces, reserved for future screen-printing, presents an opportunity to practically evaluate the dye's performance. Assessing colour fastness, durability, and resistance to washing and light exposure can provide a comprehensive understanding of the dye's suitability for different textile applications.

The findings highlight the need for further experimentation to optimise the dyeing process, explore alternative natural dyes, and assess the dye's performance in practical applications. Following this experimentation, a one-week placement was carried out at Keracol to further examine the effects of the pH of blackcurrant dye, which also contains anthocyanins.

5.3.4 Ex 7: Project Partnership: Keracol (Blackcurrant)

Aim: This study aimed to compare textile dyeing outcomes and procedures conducted in a domestic setting with those carried out in a laboratory. It also provided an opportunity to gain further insights into the extraction of anthocyanins from food waste and the underlying chemical processes involved.

The findings and conclusions obtained from this placement served as valuable guidance for the laboratory work conducted at the University of Leeds (UoL) regarding the development of coloured filaments, as documented in Section 5.4.3.

Location: Lab (Keracol)
Collaborators: Alenka Tiddar (AT), Professor Richard Blackburn (RB)
Tools/Materials: Casein fibres, Casein twill, blackcurrant powder (BCP), blackcurrant skins (BCS), beakers, $Kal(SO_4)_2$, PH meter, magnetic stirrer, Ugolini Redkrome II laboratory dyeing machine.

Method: BCS obtained from Ribena food waste were the primary dyestuffs used by Keracol during the study. The BCS were transformed into BCP using a spray dryer to facilitate their use. Both skins and powder were tested to compare their colour strength and wash fastness. The conversion process of BCS into BCP through evaporation using a spray drying machine is depicted in Figure 56 (provided by Keracol).

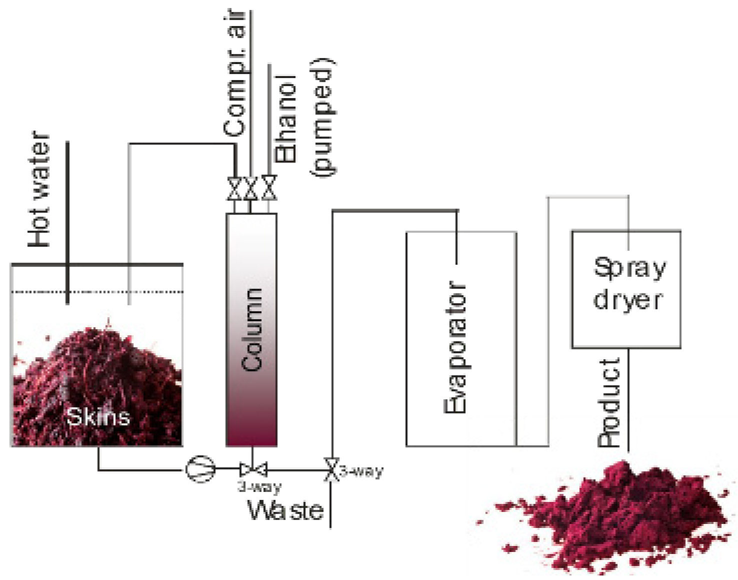


Figure 56: The process of extracting a powdered dye from BCS. (Image provided by Keracol).
Figure 57: Heidolph Instruments: Rotary evaporator used to extract powdered dye.

At Keracol, a learn-by-replication approach was adopted. Dr Alenka Tiddar (AT) conducted the initial experiments and explained the underlying chemistry. I then repeated the same process to compare the results.

All dyeing procedures at Keracol were carried out using a Ugolini Redkrome II laboratory dyeing machine. This machine consists of an isolated chamber with an inner rotating disk capable of holding up to 16 sample tubes, each accommodating a maximum of 200ml of liquid. Temperature and duration were set using a sensor that measured the temperature and initiated a timer accordingly.

The standard dyeing parameters for the machine were set at a temperature (T) of 60˚C and a time (t) of 30 minutes. Dye concentration was determined based on the mass of fabric/fibre (omf). For instance, when using 5g of fabric/fibre, a dye concentration of 1% omf equated to 0.05g, while 5% omf represented 0.25g of dye. The liquor ratio, calculated as 1:7, indicated that 1g of fibre/fabric required 7g of water. Aluminium Potassium Sulphate ($Kal(SO_4)_2$) was employed as a fixative mordant. The calculation for its usage was 1% omf (0.05g).

Tests were conducted in three batches of 12 samples each, divided between casein fibres and fabric. Each sample was tested at pH 2, pH 4, and pH 6, both with and without 1% omf $Kal(SO_4)_2$.

	Test 1: 1% omf BCP	Test 2: 5% omf BCP	Test 3: 5% omf BCS
5g Fabric	pH 2	pH 2	pH 2
5g Fabric	pH 2 + $Kal(SO_4)_2$	pH 2 + $Kal(SO_4)_2$	pH 2 + $Kal(SO_4)_2$
5g Fibre	pH 2	pH 2	pH 2
5g Fibre	pH 2 + $Kal(SO_4)_2$	pH 2 + $Kal(SO_4)_2$	pH 2 + $Kal(SO_4)_2$
5g Fabric	pH 4	pH 4	pH 4
5g Fabric	pH 4 + $Kal(SO_4)_2$	pH 4 + $Kal(SO_4)_2$	pH 4 + $Kal(SO_4)_2$
5g Fibre	pH 4	pH 4	pH 4
5g Fibre	pH 4 + $Kal(SO_4)_2$	pH 4 + $Kal(SO_4)_2$	pH 4 + $Kal(SO_4)_2$
5g Fabric	pH 6	pH 6	pH 6
5g Fabric	pH 6 + $Kal(SO_4)_2$	pH 6 + $Kal(SO_4)_2$	pH 6 + $Kal(SO_4)_2$
5g Fibre	pH 6	pH 6	pH 6
5g Fibre	pH 6 + $Kal(SO_4)_2$	pH 6 + $Kal(SO_4)_2$	pH 6 + $Kal(SO_4)_2$

Table 18: Details of all 36 tests conducted (x3 batches of 12).

The basic procedure for Test 1 was as follows:

Step 1: Weigh six sets of casein fibres or cut fabric, weighing approximately 5g each.
Step 2: Dissolve BCP in water, stirring for 10 minutes (1:7 ratio, resulting in 420g of solution consisting of 35g water per sample and 6g of BCP for the 12 samples).
Step 3: Prepare solution by adding $Kal(SO_4)_2$ (210g solution + 3g $Kal(SO_4)_2$ for 6 samples).
Step 4: Adjust the pH by dividing the solution and solution + aluminium (Al) between 3 beakers and altering the pH to 2, 4, and 6 (using formic acid and sodium hydroxide to modify pH).
Step 5: Add the solutions and fabric or fibres to the corresponding dye tubes.
Step 6: Place the tubes evenly distributed inside the dye machine and set the temperature and timer (60˚C for 30 minutes).
Step 7: Once the dyeing process is completed, remove the samples from the tubes and wash them in warm water.

Test 2 followed the same procedure as Test 1, with the only alteration being the use of a higher BCP concentration of 5% omf (0.25g of BCP).

For Test 3, measuring and preparing BCS involved sewing them into polyester pouches resembling tea bags. This setup allowed the colour to escape while effectively trapping the skins for easy removal. It should be noted that BCS and BCP had to be weighed differently because BCP is a pure colour extraction from the skins. If the skins were weighed in the same manner as the powder, it would result in lesser colour intensity. Hence, a weight-by-weight (w/w) calculation was employed to determine the appropriate amount of skins to use.

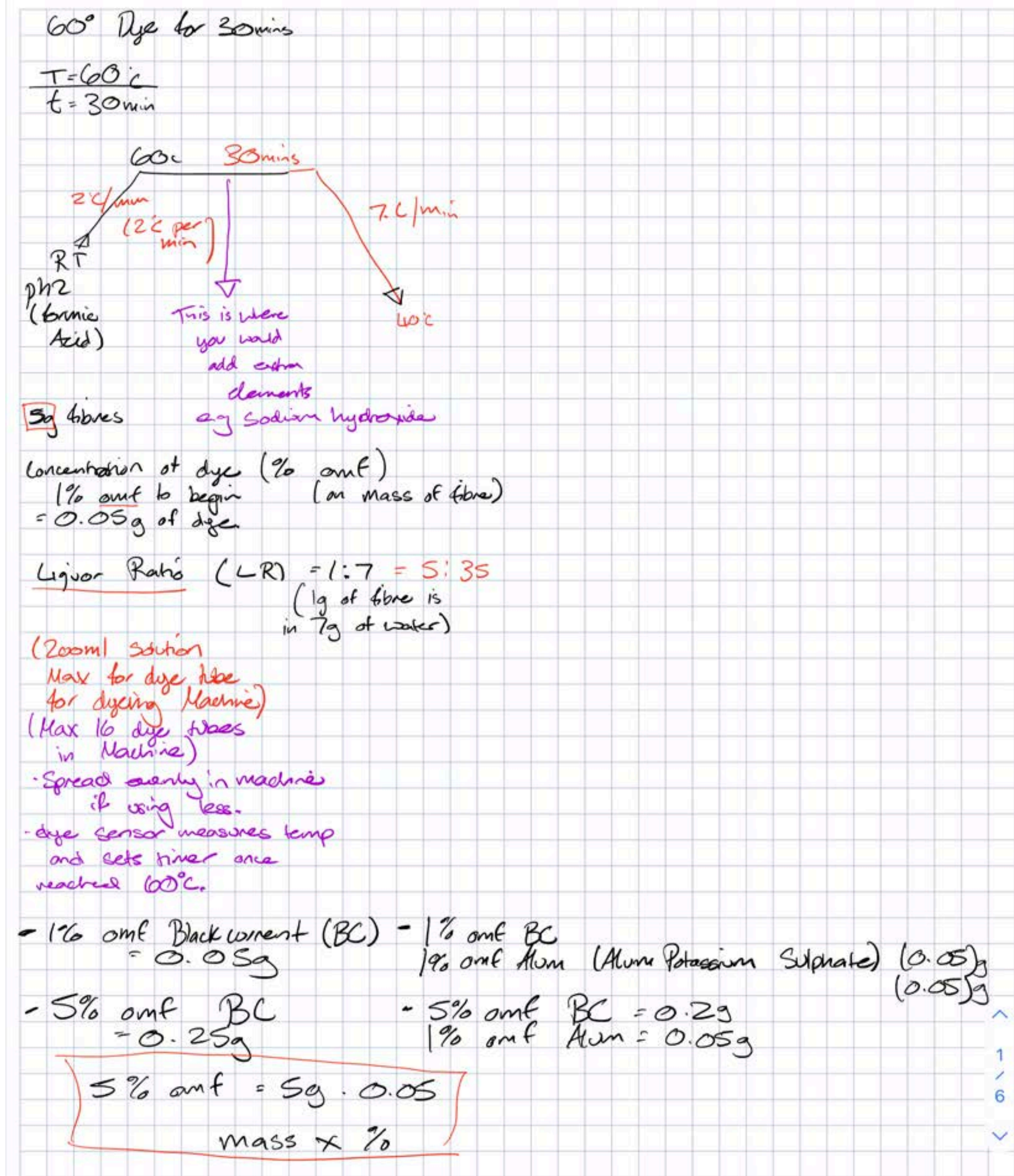


Figure 58: Lab notes from Keracol.


Figure 59: BCS measured and ready to be sewn into the pouch for dying.


Figure 60: BCS prepared and ready for dying.

100g BCS = 2.8g dye extraction (BCP)

2.8g = 100%
25g = 5% omf BCP (this would be too much to fit in each tube).
25g/2.8g = 8.93g w/w BCS (7.84%w/w)

8.93g BCS x 12 samples
150ml water
5g fabric/fibre.


Figure 61: washing samples after dyeing.

To illustrate the calculation, 100g of BCS yielded a dye extraction of 2.8g (BCP). Therefore, 2.8g represented 100% of the colour extraction. To achieve a 5% omf BCP concentration, which would be too much to fit in each tube, the following calculation was used: **25g / 2.8g = 8.93g w/w BCS.**

Hence, for each sample, **8.93g** of BCS was used. The dyeing process used 150ml of water and 5g of fabric/fibre per sample.

Colour Measurement: During the initial batch of tests, it was observed that the fabric underwent rapid colour changes upon removal from the dye tube and contact with tap water during the washing process. To compare colour changes after drying, a portion of each fabric sample was cut off and left unwashed. Once the tests were completed and the samples had dried completely, the colours of both the fabric (pre- and post-washing) and fibre samples were measured using a Spectrophotometer Datacolor 500 (Appendix 10.3).

Wash Fastness: To assess the wash fastness of the dyed samples, Washtec Colour Fastness Test Equipment was employed. A washing solution was prepared by mixing 4g of wool wash detergent (Woolite) with 1 litre of water. This solution was divided among the tests, with each test using 150ml. A multifibre fabric test strip was added to each tube, and the samples were washed at 30°C for 30 minutes. After washing, all the samples were subjected to a second round of colour measurement.

Results: Table 19 compares the results of the three conducted colour tests, including colour measurements before and after the wash fastness testing.

After thoroughly drying the samples, significant colour changes between the prewashed and washed dyed fabrics were observed. It was also evident that the fibres exhibited more colour consistency than the fabric. These results were consistent with the results of Ex 7 (5.3.4) and the use of onion skin dyes, which also demonstrated colour instability upon washing (5.3.3).

Generally, the colours of the fibres were more aligned with the prewashed fabric samples. Surprisingly, the extracted BCP yielded less robust and consistent colours than BCS. This unexpected result was likely influenced by the method used to calculate the weight of the dyestuff (w/w rather than omf).

A discussion was held among AT, RB and I to explore the possible reasons behind these outcomes. It was anticipated that colour changes would occur across different pH levels. Lower pH values (around pH3) typically result in more intense red and pink hues, transitioning to shades of blue as the pH increases. As the fabric samples turned blue upon rinsing, it could be inferred that the pH of the tap water contributed to this change. This observation also suggests that the dye may not have fully penetrated the fabric, leaving the surface dye vulnerable to external factors.

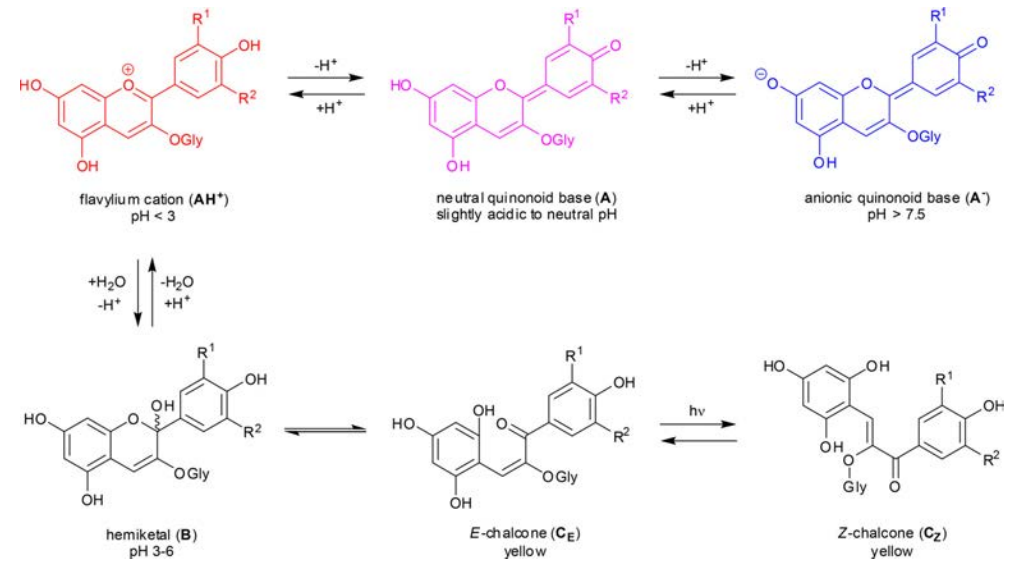


Figure 62: Effect of pH on anthocyanin structure and resultant colour. (Rose, Cantrill et al., 2018)

Figure 62 illustrates the effect of pH on anthocyanins, particularly regarding the removal or addition of H+ ions (a positively charged particle derived from a hydrogen atom that has lost its electron). The higher the pH (H+ ion removal), the more the anthocyanin tends towards its blue form. In the context of the dye samples, this indicates that the dye did not undergo degradation, which would instead result in a yellow or brown colour.

Anthocyanins undergo physiochemical degradation in vivo and in vitro (Houghton, Tidder, et al., 2024). Various factors, such as structure, pH, temperature, light, oxygen, metal ions, intramolecular association, and intermolecular association with other compounds, can affect the colour and stability of anthocyanins (Kong, Chia et al., 2003). These compounds can act as pH indicators, showing red or pink colours in acidic solutions (pH < 7), purple colours in neutral solutions (pH ≈ 7), greenish-yellow colours in alkaline solutions (pH > 7), and becoming colourless in highly alkaline solutions where the pigment is completely reduced (Fossen, Cabrita et al., 1998). The perceived colour of both fabric and fibres can also be influenced by the physical morphology of the materials, including factors such as size, shape, surface texture, and volume, all of which can affect dye absorption.

Colour fastness results revealed that both fibres and fabric experienced colour changes during the wash fastness testing. Notably, the fabric exhibited more noticeable colour changes, tending towards brighter shades of blue, while the fibres exhibited a range of darker purple/blue shades. Staining was also observed, primarily on natural fibres such as regenerated cellulose and cotton. Interestingly, the fibres demonstrated better colour retention compared to the fabric. Regarding pH, staining differences were minimal, with all dyeing liquors (pH2, pH4, and pH6, with and without $KAl(SO_4)_2$) causing blue staining on regenerated cellulose and cotton and yellow staining on nylon. (See Appendix 10.3 for full results).

Image 63: Wash fastness results of 7.84% w/w BCS PH2, (1% Alum) on casein fabric (Appendix Table 12 for full results).

Reflection: Working in a lab-based environment proved to be more practical and efficient when working with colour compared to domestic settings. The lab's methods for creating dyes were more consistent and reproducible, contrasting the subjective visual measurements employed domestically. The laboratory dye machine offered a more practical solution for small-scale testing of colours and exploration of dye formulas, enabling the rapid collection of a substantial amount of data in a short space of time. This improved efficiency and facilitated the exploration of various dyeing parameters.

Using powdered dye instead of solid dyestuff, such as skins, offered several advantages regarding process efficiency. Working with a powdered dye proved to be a quicker, easier, and less

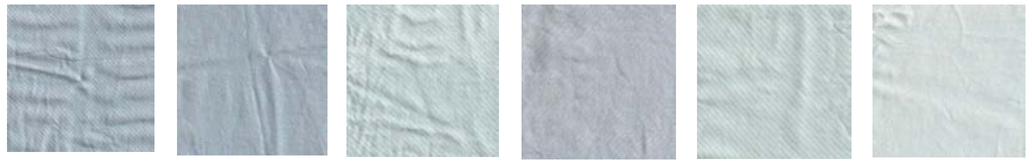
	1% omf BCP PH2	1% omf BCP PH2 1% Alum	1% omf BCP PH4	1% omf BCP PH4 1% Alum	1% omf BCP PH6	1% omf BCP PH6 1% Alum
Fabric (pre wash)						
Fabric (Post wash)						
Fibre						
	5% omf BCP PH2	5% omf BCP PH2 1% Alum	5% omf BCP PH4	5% omf BCP PH4 1% Alum	5% omf BCP PH6	5% omf BCP PH6 1% Alum
Fabric (pre wash)						
Fabric (Post wash)						
Fibre						
	7.84% w/w BCS PH2	7.84% w/w BCS PH2 1% Alum	7.84% w/w BCS PH4	7.84% w/w BCS PH4 1% Alum	7.84% w/w BCS PH6	7.84% w/w BCS PH6 1% Alum
Fabric (pre wash)						
Fabric (Post wash)						
Fibre						

Table 19: Dye results of Blackcurrant Skins (BCS) and Blackcurrant Powder (BCP) on casein fabric and fibres.

energy-intensive approach. In contrast, creating domestic dyes typically involves the extraction of colour using a hob and a saucepan, which presents challenges when conducting small-scale tests. Domestic dyes often need to be prepared in larger batches, requiring more water, increased energy consumption for heating over a more extended period, and a larger amount of dyestuff, making it challenging to carry out efficient small-scale testing and gather sufficient data.

The findings of this section have raised further inquiries into the chemical composition of the casein fabric currently employed. Even on a laboratory scale, attaining colour consistency has proven challenging for AT and RB, who are experienced professionals in green chemistry and natural dyes. Nevertheless, achieving consistency with natural dyes presents a common industry-wide challenge, and the results showcased here offer promising prospects. Building on the insights gained from this lab visit, Keracol has continued investigating the impact of pH and other factors on the behaviour of anthocyanins present in BCP dyes when applied to casein materials and wool.

5.3.5 Ex 8: Screen-Printing On Commercial Casein Fabric

Aim: This study explores screen-printing inks derived from food waste. The aim is to identify a suitable screen-printing medium that enables a broader range of decorative techniques to be employed in the design of compostable garments.

Location: Kitchen
Collaborators: Kercol
Tools/Materials: Casein twill, aluminium pan, frying pan, measuring cylinder, pipette, roller, casein powder, gum tragacanth, Permaset, screen-printing frame, stencil paper, turmeric powder, beetroot powder, avocado dye, avocado seed (pre-colour extraction), avocado seed (post-colour extraction), red-onion skin dye.

Method: This range of experiments involved trialling three screen-printing mediums: Casein powder, Gum tragacanth (GT), and Permaset. Casein, a powder derived from milk, has a long history of use in paint production, dating back to ancient Asian cave paintings (Johnson, 2021). While no literature indicates its applicability as a textile medium, I first tested casein powder due to its ready availability and the potential for minimising additional resource consumption if a successful formula could be developed.

Gum tragacanth, a water-soluble polysaccharide commonly used as a thickening agent, emulsifier, and stabiliser in the food industry, has also been explored as a screen-printing medium by designers and textile researchers. Ellams investigated this ingredient in her PhD thesis, focusing on environmentally conscious fashion and responsible colouration techniques (Ellams, 2016). Ellams used gum tragacanth as a thickening agent to create natural screen-printing inks using Eucalyptus as the primary dyestuff.

Permaset, on the other hand, is a water-based, solvent-free screen-printing medium produced with non-toxic ingredients and renewable energy. Their textile inks and screen-printing mediums are certified by Oeko-Tex and Global Organic Textile Standards (GOTS) and approved by the Soil Association (Permaset, n.d.).

The samples were printed at home using a domestic screen-printing kit obtained from Etsy. A simple leaf design was hand-cut from stencil-cut film, featuring thin lines and larger open areas to assess how well the ink passes through different spaces. Before screen-printing, each ink was tested using a small roller to evaluate colour and texture, minimising wastage if the colour did not adhere or the formula required adjustment. The roller tests were not washed after drying to enable comparison with the washed, screen-printed samples.

After printing, each sample was air-dried and pressed using a domestic iron set at the highest temperature (approximately 230°C), with a lightweight calico placed between the sample and the iron. This pressing process was repeated twice for 2 minutes each time. The samples were then hand-washed with warm water and a delicate, hand-wash detergent before being air-dried.

Figure 64: Testing of screen-printing ink.
Figure 65: Result of screen-printing with turmeric ink.

The samples were organised in batches per experiment, as indicated in Table 20. Each screen-printing ink employed slightly different formulas and processes depending on the printing medium and dyestuff used. For instance, turmeric powder could be directly added to the screen-printing medium and dissolved to form the ink. However, non-powdered dyestuffs required an initial colour extraction in water, creating a liquid dye. This dye was then reduced over low heat to thicken and reduce, as otherwise, the inks would be too watery. Leftover dye from previous experiments was utilised as a starting point for these inks where possible. The reasons for selecting each specific formula/process are discussed in the results section.

The challenge of working with liquid dyes compared to powdered pigments became apparent early in the investigation. To address this issue, I contacted Keracol to explore potential solutions that could be implemented outside of a laboratory setting. Since specialised equipment is necessary for evaporating and converting dye into powder form, Keracol sent me 2x 100g of powdered avocado seed for testing. One bag contained a post-colour extraction with particle sizes ranging from 200-500 microns, while the other bag contained a chunkier, pre-colour extraction (size unknown). Unfortunately, these powdered dyes still required an initial colour extraction and could not be directly dissolved into a liquid or paste.

Figure 66: Avocado dyestuff prepared in three different ways. (Full skins and pits, pre-colour extraction and post-colour extraction).

Figure 67: Turmeric, onion and avocado scrennprinting inks tested on avocado dyed casein twill.

Batch	Sample range	Printing medium	Dyestuff	Formula	Process
SP1	1	Casein	Avocado (dye)	100ml Avocado Dye, 5g casein powder	Components are mixed for 2 hours until dissolved Ink was applied to casein fabric using roller and paint-brush.
SP2	2.1	Gum Trag-acanth	Avocado (dye)	250 - 650ml Avocado dye, 14g (1 tablespoon) GT	Components are mixed in a blender until smooth. A further 400ml of dye was added to the blender in increments of 200ml to reach desired viscosity. An initial test was applied to casein fabric using roller. A second test was conducted using the silk screen, stencil and squeegee.
	2.2	Gum Trag-acanth	Turmeric (powder)	100ml water, 1.5g GT, 2.4g Turmeric	1g of GT was initially added to 100ml of boiling water and blended before adding a further 0.5g to reach the desired viscosity. Altogether, 60g of paste was made to which 4% (2.4g) of colour was added. An initial test was applied to casein fabric using roller. A second test was conducted using the silk screen, stencil and squeegee.
SP3	3.1	Permaset	Turmeric (powder)	2.4g Turmeric, 5ml Water, 60g Permaset	5ml of water is added to turmeric powder to dissolve making a concentrated ink. This ink as added to the Permaset and mixed in until smooth. An initial test was applied to casein fabric using roller. A second test was conducted using the silk screen, stencil and squeegee.
	3.2	Permaset	Avocado seed (Pre colour ex-traction)	150ml avocado dye, 30g Permaset 3.2.1: 0.2ml colour, 3.2.2: 0.6ml of colour, 3.2.3: 2ml colour, 3.2.4: 4ml colour, 3.2.5: 5ml colour, 3.2.6: 5ml colour.	The Avocado dye is reduced in a small pan over a high heat for 40 mins until a thickened, concentrated liquid of 6ml is achieved. The dye is cooled and added in incre-ments the Permaset to test colour strength. 5 initial tests were applied to casein fabric using roller to test concen-tration. A final test was conducted using the silk screen, stencil and squeegee.
	3.3	Permaset	Beetroot (powder)	3.5g Beetroot, 5ml water, 30g Permaset	5ml of water is added to beetroot powder to dissolve making a concentrated ink. This ink as added to the Permaset and mixed in until smooth. An initial test was applied to casein fabric using roller. A second test was conducted using the silk screen, stencil and squeegee.
	3.4	Permaset	Red Onion (dye)	300ml red onion skin dye, 30g Permaset 3.4.1: 2ml colour, 3.4.2: 4ml colour, 3.4.3: 6ml colour, 3.4.4: 8ml colour, 3.4.5: 10ml colour, 3.4.6: 12ml colour 3.4.7: 12ml colour	The onion dye is reduced in a small pan over a high heat for 40 mins until a thickened, concentrated liquid of 12ml is achieved. The dye is cooled and added in increments the Permaset to test colour strength. 6 initial tests were applied to casein fabric using roller to test concentration. A final test was conducted using the silk screen, stencil and squeegee.

Table 20: Formula and process for the making of various screen-printing inks.

Results: SP1: The conventional method of making milk paint involves using a powdered dye. However, since I was working with a liquid dye, I initially prepared the casein-based ink by adding casein powder gradually until the desired viscosity was achieved. When the casein was added to the dye, it was observed that the formula quickly lost its colour and turned a very pale pink. Upon testing the ink with a small roller, a pale colour was visible, but the texture of the ink dried hard, distorting and curling the fabric.

SP2.1: Inspired by Ellams work with GT (Ellams, 2016), an initial paste was made using a ratio of 1 part GT to 4 parts water. However, this ratio proved to be too high as the paste was excessively thick and unusable. An additional 400ml of dye was added to adjust the viscosity and improve consistency. The resulting ink had a jelly-like texture and exhibited visible air bubbles. While the ink printed reasonably well, it appeared faint in colour. After drying and washing, the colour faded further, leaving a pale pink hue. The print also had a noticeable texture, which may be attributed to the use of a thin fabric.

SP2.2: Another test was conducted using GT with turmeric powder to explore if a powder-based dye could produce a more vibrant colour. In this trial, a lower ratio of GT to water and a 4% concentration of turmeric powder was used. Working with a powder instead of a liquid dye allowed for a more precise colour ratio determination, enabling more consistent and controllable results. The turmeric powder did not mix perfectly with the GT, resulting in the final ink having a grainy appearance. Fortunately, these particles did not pass through the screen and were not visible on the printed fabric. As anticipated, this ink yielded a brighter colour but still fell short of the desired vibrancy. The print retained a stiffness even after washing and drying.

SP3.1: To replicate the ratio used in test SP2.2, 2.4g of turmeric was combined with 60g of Permaset. Based on the results of the previous test, the decision was made to dissolve the turmeric in hot water before adding it to the print medium, aiming for a smoother paste. This technique proved successful, and the resulting Permaset ink resembled a traditional screen-printing ink in terms of texture and viscosity. When printed, the colour was significantly more vivid, exhibiting a darker shade of yellow. The ink passed smoothly through the screen and stencil without any bleeding and resulted in an even distribution of colour. Although a slight texture could still be felt after washing, it was less stiff than the previous samples.

SP3.2: In the creation of the following screen-printing inks, both pre-colour and post-colour extraction avocado seeds provided by Keracol were first tested as dyes and compared to the previous avocado dyes prepared using the full skins and seeds (5.3.1). It became apparent that the colour extracted from the seeds alone was less intense, but there was little difference observed between the two forms of avocado seeds. The initial plan was to use the stronger seed-only dye; however, since no visible differences were observed, the pre-colour extraction was chosen to test as an ink.

In its current form, the liquid dye was too watery to be added to the Permaset without altering its consistency. The dye was reduced from 150ml to 6ml To maximise colour intensity while minimising the liquid content. This reduction resulted in a more concentrated and vibrant ink.

Figure 68: Turmeric ink made with Permaset (left) and turmeric ink made with GT (right).

Figure 69: Preparation of SP3.2 (avocado ink) – mixing of reduced dye into Permaset).

Small increments of ink were added to the Permaset at a time and tested on fabric to assess the strength of the colour. The results ranged from a pale, dusty pink to a deeper shade of blush, surpassing the original dye in darkness. Once the full 6ml of dye was combined with the Permaset, the ink was tested on the stencil, yielding a much deeper print. The ink passed through the screen consistently without any colour bleeding.

SP3.3: Following the success of both inks using Permaset, I sought to compare the outcomes of more powder and liquid-based inks employing this medium. During an online search for powdered herbs and spices with natural colours, I discovered powdered beetroot, commonly used as a natural food colouring agent. Building upon the process outlined in SP3.1, beetroot powder was mixed with water to create a paste before incorporating it into the Permaset. The initial ink displayed an incredibly bright and rich pink hue, which transferred well to the fabric during the initial roller test. The ink passed through the screen smoothly on the second test, producing a strong and consistent colour. However, upon washing, a significant portion of the colour faded, particularly around the edges of the design, leaving a much paler shade of pink.

Three days after preparing the ink, I observed that the remaining ink had turned dark brown, indicating its unsuitability for long-term storage or use beyond the initial trials. To conduct a comparative test, I also produced a small batch of dye using beetroot powder to ascertain whether the same vibrant colour could be achieved on the fabric and whether the colour retention would differ from that of the ink after washing. Surprisingly, the colour did not adhere well, and the fabric emerged from the dyeing process in a pale shade of yellow.

SP3.4: After extensively exploring red onion skin dyes and the challenges of achieving a stable colour (5.3.3), I decided to test it as a screen-printing ink. In general, inks have exhibited more consistent behaviour than dyes, potentially due to the addition of the Permaset medium. I gradually added 2 ml of reduced onion dye to the Permaset medium to assess the colour strength. Overall, the resulting ink produced a soft, dusty pink hue akin to the avocado ink.

Since this test was conducted later in the project, I utilised a different, larger stencil. To assess the outcomes, the design was printed twice, once on an avocado-dyed fabric and once on an onion-dyed fabric. When printed on the onion-dyed material, the resulting print exhibited a significantly darker colour than on the lighter avocado-dyed fabric. Although some bleeding was observed in larger areas of the design where more ink was applied, it was not particularly noticeable once

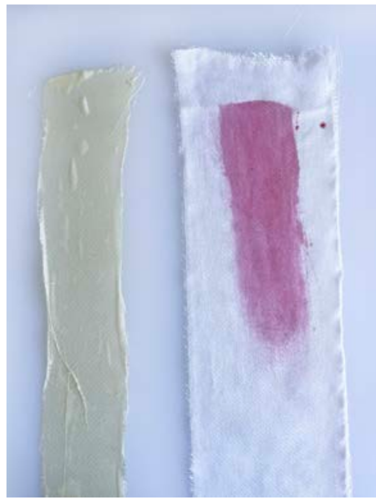


Figure 70 - 72: Preparation of SP3.3 (beetroot ink) – mixing of bee root powder into Permaset.
Figure 73: Comparison of beetroot screen-printing ink to the colour of beetroot dyed fabric.

the print had dried. Due to the larger size, the texture of the print was more pronounced on the soft, thin fabric.

Reflection: Permaset was the most effective screen-printing medium when combined with various natural dyes. It yielded a smoother and more consistent paste and resulted in prints with stronger colours and better colour retention than casein powder and GT.

Screen printing would have been more suitable for heavier fabrics. The commercially sourced casein fabric used in this study was thin and lightweight, leading to a distinct texture alteration when surface prints were applied. Consequently, smaller prints exhibited a superior overall finish to larger prints, which had a more pronounced, crisp texture that contrasted with the soft casein fabric. Additionally, larger prints affected the fabric's drape and were more prone to bleeding around the edges, although the ink thickness also played a role in this outcome.

It became evident that working with powdered dyes would have enhanced the methodology and facilitated more consistent results. The advantages of using a post-colour, powdered dye extraction are that it eliminates the need to manually extract the dye from a liquid and reduce it to ink, as well as avoiding adding additional liquid (dye) to the screen-printing medium, which already possesses the desired consistency.

A deeper understanding of natural dyes has been achieved through screen-printing experimentation. In the case of turmeric and beetroot dyes, it was observed that the Permaset medium produced brighter colours compared to other mediums.

5.3.6 Ex 9: Knitting With Casein

Aim: The objective of this initial textile construction test was to evaluate the ease or difficulty of working with commercially available casein yarns and gain a better understanding of their properties, including fibre shedding, strength, and tenacity. This activity required minimal equipment (only knitting needles and yarn) and could be efficiently conducted at home until access to weaving facilities and expertise was available later in the project.

Location: Home
Collaborators: N/A
Tools/Materials: Knitting needles (gauges 4mm, 5mm, 6mm, and 7mm), casein yarns.

Method:
Four knitted samples were created using bulky casein yarn with 4mm, 5mm, 6mm, and 7mm needle gauges. All samples were knitted in a purl stitch, consisting of 13 rows and 16 stitches per row. This swatch size was selected to provide a sense of working with the yarn and to facilitate handling and assessment as a knitted material. Testing different needle gauges allowed for the exploration of how the yarn responded to varying pressure levels (e.g., tightly wound or looser stitch) and enabled a comparison of the size and stretch of each sample.

Figure 74: Knitting with commercial casein yarn.

Results: 4mm: Final sample size - 8x7cm. The smallest sample proved to be the most challenging to knit. The smaller needle gauge provided less space for casting on the next stitch, resulting in friction between the yarn and the needle. It was observed that the yarn shed heavily when handled, although no yarn snapping occurred under pressure. Once the sample was cast off the needle, it exhibited a fluffy texture. Overall, the yarn felt incredibly soft and lustrous, with a slight stretch.

5mm: Final sample size - 10x9cm. The next size up in needle gauge made working with the yarn much more manageable. A slightly looser tension reduced friction between the needle and yarn, although occasional friction was still noticeable. A significant amount of fibres were shed during knitting, resulting in a fluffy texture in the final swatch. However, the yarn remained robust, and no yarn snapping was observed. Similar to the previous sample, this swatch was remarkably soft and lustrous. The looser nature of this knit allowed for greater stretch in the swatch.

6mm: Final sample size - 11x10cm. This swatch size was found to be the most enjoyable to knit. The weight of the yarn paired well with the gauge of the needle, creating a slightly looser and more open-knit, which added flexibility and a lighter feel to the swatch compared to the previous two samples. This swatch exhibited more significant stretch and felt soft and breathable against the skin.

7mm: Final sample size - 12x11cm. The largest swatch displayed a visibly looser construction and started to feel slightly too loose for the weight of the yarn. This swatch demonstrated high flexibility and began to exhibit more drape and elasticity compared to the other swatches.

Reflection: The knitting process using commercial casein yarns in different needle gauges provided valuable insights into the material properties and characteristics of the yarn. Conducting small, knitted samples at home allowed for a hands-on exploration of the yarn's behaviour and ease of use. The results of this test revealed interesting observations and considerations for future experimentation.

Throughout the process, it became apparent that the casein yarns presented some challenges. As observed with the casein fibres, the yarns were incredibly slippery and shed heavily during knitting. Feedback on these observations was shared with JH and HAG, enabling a shared understanding of existing casein materials.

The knitted samples revealed that the casein yarns have remarkable softness and would produce beautiful knitwear. The material shows potential for creating comfortable and luxurious garments against the skin. Overall, this initial exploration of working with commercial casein yarns through small knitting samples provided valuable insights into the material's properties and suitability for future textile projects.

5.3.7 Ex 10: Weaving With Casein: Exploration

Aim: This activity aimed to evaluate the ease or difficulty of working with commercial casein yarns and better understand their properties. Unlike knitting, which focused on one type of casein yarn, this activity explored all four weights of casein yarn to compare their properties and examine the results regarding weave structure and weight. The research was conducted collaboratively with HAG in her studio, and feedback was shared with JH regarding suggested improvements for the fibre and filament.

Location: Studio (HAG)
Collaborators: HAG
Tools: 4-shaft table loom, warping mill, shuttles, raddle, reed, threading tools, undyed casein yarns (various weights).

Method: This research was conducted using a hand table loom over two days. The first day was dedicated to learning the setup and warping process of the loom. On the second day, various woven structures and threading drafts were explored using different yarn weights. For warping the loom, a lightweight yarn was selected. This decision was made to enable the creation of a range of samples with different weights and textures. Using a heavier yarn for the warp would have limited the diversity of the samples. Small swatches were produced to test different weave types and weight combinations using the same continuous warp.

Results: Twelve samples, approximately 15 x 8cm in size, were created due to this two-day experimentation. Table 21 presents the weave and threading draft details for each sample. A diverse range of weaves, including plain, twill, hopsack, herringbone, and satin, were explored using different weights and styles. The aim was to understand how the casein fibre behaved in various scenarios and examine the different weave patterns' overall visual appearance, tactile qualities, and texture.

The overall aesthetic of the samples was highly pleasing, showcasing materials that appeared robust and relatively sturdy, exhibiting a silky sheen reminiscent of luxurious fibres like cashmere or merino wool. Depending on the specific weave structure, the weight of the samples indicated suitability for heavier garments such as jackets or trousers, in contrast to the commercially available casein fabric, which tends to be very thin.

These findings highlight the potential of casein as a viable alternative for creating durable, high-quality textile products. The exploration of weave structures allowed for a comprehensive assessment of the casein fibre's versatility and ability to contribute to producing garments with distinct aesthetics and functional characteristics.

Figure 75: Dressing the loom.

Figure 76: Dressing the loom.

Figure 77: Weaving with commercial casein yarn. Plain weave.

Figure 78: Weaving with commercial casein yarn. Hopsack weave.

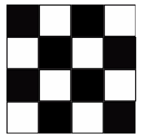
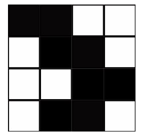
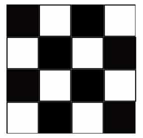
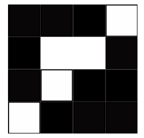
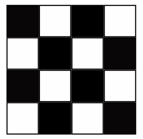
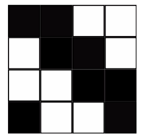
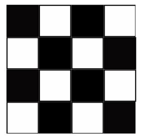
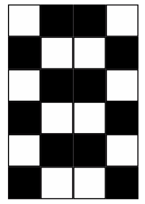
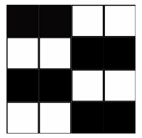
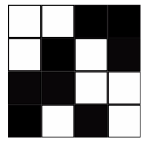
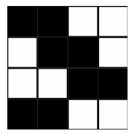
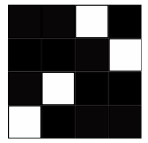
Weave	Yarn Weight (Weft)	Threading Draft	Image	Weave	Yarn Weight (Weft)	Threading Draft	Image
Plain	Light weight			Twill	Lace weight		
Plain	Mid weight			Twill (Denim)	Light weight		
Plain	Bulky weight			Twill	Mid weight		
Plain	Lace weight			Hopsack	Bulky lace + Lace weight	 L B L L B L	
Twill	Lace weight			Her-ringbone	Mid weight		
Twill	Lace weight			Satin	Lace weight		

Table 21: Results and threading draft – weaving with yarn.

Reflection: The first-hand experience of weaving provided valuable insights into the decision-making process involved in textile production. This experience shed light on the significance of selecting appropriate yarn weights for both the warp and weft, as they directly impact the overall appearance and texture of the fabric. Moreover, it allowed for understanding the time and effort required for different threading drafts. Although the initial experimentation employed only white yarn, it served as a foundation for envisioning the incorporation of colour and pattern in subsequent stages of the project.

In working with casein fibres on the loom, the observations confirmed a hypothesis derived from previous hand-knitting experiments: the fibrous nature of casein resulted in a notable shedding tendency. However, despite this shedding, the warp demonstrated good strength and resilience, with no snapping or thinning throughout the weaving process.

These samples serve as a basis for further exploration, as detailed in Section 5.3.8, where they are thoroughly examined to inform the design of a final range of woven samples (5.3.9). A more comprehensive understanding of the potential applications and limitations of casein fibres in woven textiles can be achieved by reflecting on these initial samples' characteristics, aesthetics, and practical implications. This knowledge was used to inform subsequent design decisions and contribute to developing a refined and cohesive collection of woven fabrics.

5.3.8 Ex 11: Weaving With Casein: Sample Development

Aim: This experimentation aimed to build upon the previous weaving trials and further develop them for a range of final samples incorporating colour. The objective was to expand the scope of the previous experiment by exploring the integration of colour within the woven fabric, thereby enhancing its aesthetic appeal and potential applications in design. By incorporating different dyeing techniques and exploring the interaction between colour and various woven structures, this research sought to advance the understanding of how colour influences the overall visual impact and texture of the woven textiles.

Location: Studio (HAG)
Collaborators: HAG
Tools/Materials: 4-shaft loom, warping mill, shuttles, raddle, reed, threading tools, undyed casein yarns (various weights), avocado dyed casein yarns (various weights), onion dyed casein yarns (lace weight), screen-printing frame, avocado screen-printing ink, avocado dye, onion dye.

Method: To further inform the development of the final woven samples, it was determined that a small range of materials would be woven before their production. This allowed for quick tests comparing the weight and structure of different weave types against the commercial casein fabric. These tests considered the developed screen-printing inks, the exploration of more complex weaves, and their potential incorporation into future designs.

Following the initial weaving and documentation of swatches described in Section 5.3.7, three preferred swatches were chosen to develop on a larger scale for further assessment. The selection process involved discussions with HAG, where the preferred woven structures were reviewed and agreed upon. The selected samples included the Satin weave, Hopsack weave, Herringbone weave, and a strip of plain weave for testing purposes. Each weave was chosen to contrast texture and weight, offering opportunities to explore various combinations of yarn and colour.

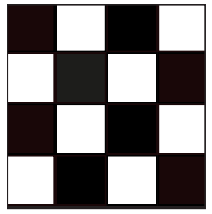
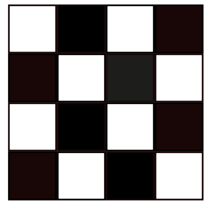
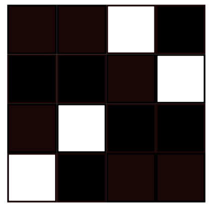
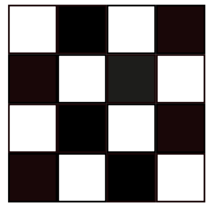
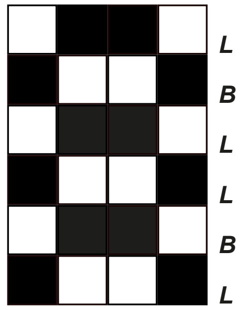
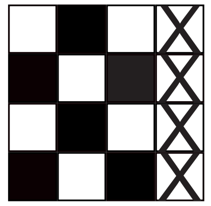
Sample 1 **Weave**: plain **Warp**: Light weight **Weft**: Light weight		Sample 4 **Weave**: Huck lace **Warp**: Light weight **Weft**: Bulky weight	
Sample 2 **Weave**: Satin **Warp**: Light weight **Weft**: Lace weight		Sample 5 **Weave**: Huck lace **Warp**: Light weight **Weft**: Light weight	
Sample 3 **Weave**: Hopsack **Warp**: Light weight **Weft**: Bulky weight + Lace weight		Sample 6 **Weave**: Moch Leno **Warp**: Light weight **Weft**: Bulky weight	

Table 22: Details of x6 woven samples.

Screen-printing test: To evaluate the compatibility of the developed screen-printing inks with the fabric's slightly textured surface, a screen-printing test using avocado ink was conducted on samples one and two. Using the initial leaf stencil allowed for an assessment of the ink's performance in thinner areas of the design.

Dye test: As a final colour assessment before designing the ultimate samples, two 1-inch strips were cut from the ends of samples one, two, and three. These strips were then tested in a red-onion skin and an avocado dye bath, utilising the pre-colour avocado extraction provided by Keracol. Until this point, only single strands of yarn had been tested (5.3.3), prompting an exploration of how the dye interacts with different woven structures and whether the weave influences the resulting colour.

Results: These initial samples presented diverse weave structures, offering a rich spectrum of possibilities to explore and analyse from a garment perspective. Each structure carried unique attributes and characteristics that prompted essential questions and considerations. Among the prominent inquiries were how these various weave structures influenced material weight, handle, and the ability to receive dyes or surface prints.

Moving through the sampling process, HAG provided feedback on working with the yarns at each stage. Her initial observations were:

"The yarn is soft, smooth, and lustrous. It comes in various weights and appears strong enough for warp and weft. The yarn does appear to be quite fluffy despite the silkiness of the fibres. Dyed yarns have a smoother quality." (HAG)

Samples 1-3 provided solid, tightly woven structures suitable to many garments, such as a coat, jacket, trousers, or skirt. These were the primary samples to be taken forward due to their versatility and suitability to different garments. Samples 4-6 are classed as fancy weaves and were intentionally created to be thinner and looser in structure with ease of degradation in mind. The samples had more of a lace or pointelle look and would be suitable in place of light knitwear such as a woven sweater or cardigan.

After weaving the samples, HAG commented:

"The yarn warped easily and smoothly with no breakages. Minimal fibres were released while warping. The yarn is quite bulky for the count, so filled the warping board quickly. The yarn was easy to transfer to the loom, wound on smoothly and threaded easily. Despite the silky texture, the yarn tied on well; the knots did not slip loose. As described, the yarn is silky yet textured enough to provide grip." (HAG)

Figure 79:Sample 3 (Hopsack).
Figure 80: Samples 3 (hopsack) 1 (Plain) and 2 (Satin).
Figure 81: Samples 6 (Moch Leno), 5 (Huck Lace) and 4 (Huck lace).

Figure 82: Sample 2 (Satin weave).

Screen-printing: As shown in Figures 83 and 84, the flatter, plain weave took the ink much better than the satin weave, which has more texture. It is visible on both weaves that the ink struggled to pass through the screen on thinner areas of the design, leaving a patchy finish. The ink did not appear to bleed into the fabric (as it did in places on the casein twill).

Figure 83:Avocado Screen-printint ink on plain weave.

Figure 84:Avocado Screen-printint ink on satin weave.

Dye Tests: Regarding the dyeing process, the results showed no significant colour variation between different weaves when using both onion and avocado dyes. The onion dye remained true to its original colour, producing a purple-brown shade, while the avocado dye yielded a surprisingly pale outcome. This avocado dye bath appeared different from previous batches, being more orange in colour, possibly due to the use of crushed avocado pits provided by Keracol. Usually, a combination of skins and pits has been used to create dyes, so it could have been that pits alone provide less colour. However, the colour (although limited) held well once washed, demonstrating good colourfastness.

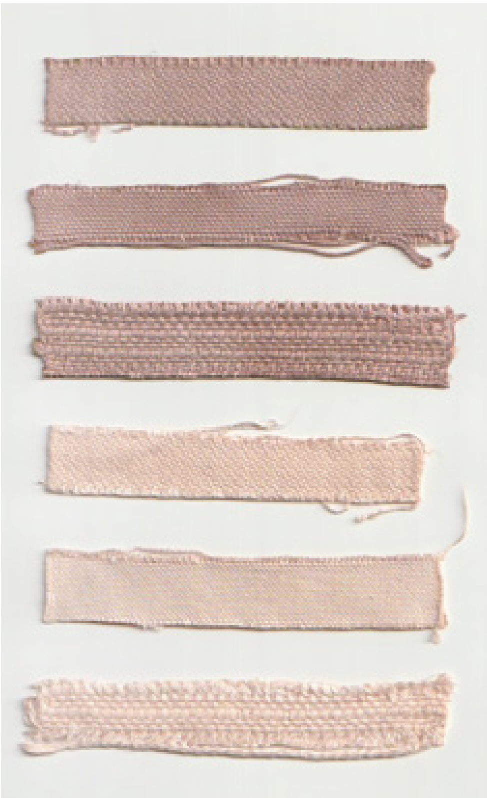


Figure 85: Onion dyed (top 3) and avocado (pre-colour extraction) dyed (bottom 3)

Reflection: Throughout the sampling process, HAG's feedback provided valuable insights into working with the yarns at each stage.

The results obtained from the experimentation with printing, dyeing and weaving techniques have provided valuable insights for developing final samples. The observations and feedback from HAG have guided the selection of swatches for further exploration, considering weight, pattern, and structure variations. The shedding tendencies of the fibres and the potential for snags in tighter weaves required consideration in the design and production of larger pieces. Overall, these results contribute to a deeper understanding of the yarn's properties and behaviour throughout the dyeing and weaving processes, informing future design decisions and enhancing the potential for creating varying qualities of woven garments.

5.3.9 Ex 12: Weaving With Casein: Final Woven Samples (Commercial)

Aim: This study evaluated the characteristics and performance of various woven fabric samples produced using different casein yarn weights and weaving techniques. Following a range of previous experiments focusing on technique, the objective was to assess their handle, appearance, durability, and resource requirements within the context of the regenerative design framework. Design features such as fringing were explored as a finishing method, eliminating the need for sewing/hemming.

Location: Studio (HAG)
Collaborators: HAG
Tools: Computerised 24-shaft dobby loom, warping mill, shuttles, raddle, reed, threading tools, casein yarns (various weights), casein yarns (avocado dyed, various weights), casein yarns (onion dyed, lace weight),

Yarn 1.A: Avo Dyed Laceweight

Yarn 1.B: Avo Dyed Laceweight

Yarn 1.C: Onion Dyed Laceweight

Yarn 1.D: Keracol Dyed Laceweight

Yarn 2.A: Avo Dyed Bulky weight

Yarn 2.B: Ecru bulky weight

Yarn 3: Ecru Weight 16/14

Yarn 4: Ecru Weight 24/4

Figure 86: Commercial yarns used in final samples.

Method: Considerations regarding colour and pattern were addressed and applied to a final sample strip. A skein of lace-weight yarn was dyed in an avocado dye bath (yarn 1.D), and another skein was dyed in a red-onion bath (yarn 1. C). These skeins were handed over to HAG along with a cone of undyed lace weight yarn, a cone of undyed bulky yarn (yarn 2. B), a cone of light weight yarn (yarn 4) and a cone of mid-weight yarn (yarn 3). Following the established dyeing procedure, HAG independently prepared a batch of avocado dye at her home and dyed yarns 1. A, 1. B, and 2. A. (Refer to Figure 86)

These dyed yarns were subsequently utilised to create a final test strip of weave structures exploring colour and the range of final samples. For the test strip, HAG opted to use a 24-shaft computerised dobby loom to give a more comprehensive range of options for cloth construction. A standard sample size of 11 inches was selected for the warp, allowing enough surface to assess material properties/appearance once woven. The undyed light weight yarn (yarn 4) was used to set up the warp. This yarn was explicitly chosen to reduce bulk (potentially resulting in a faster degradation time) whilst still being strong enough to withstand the pressure of being on the warp.

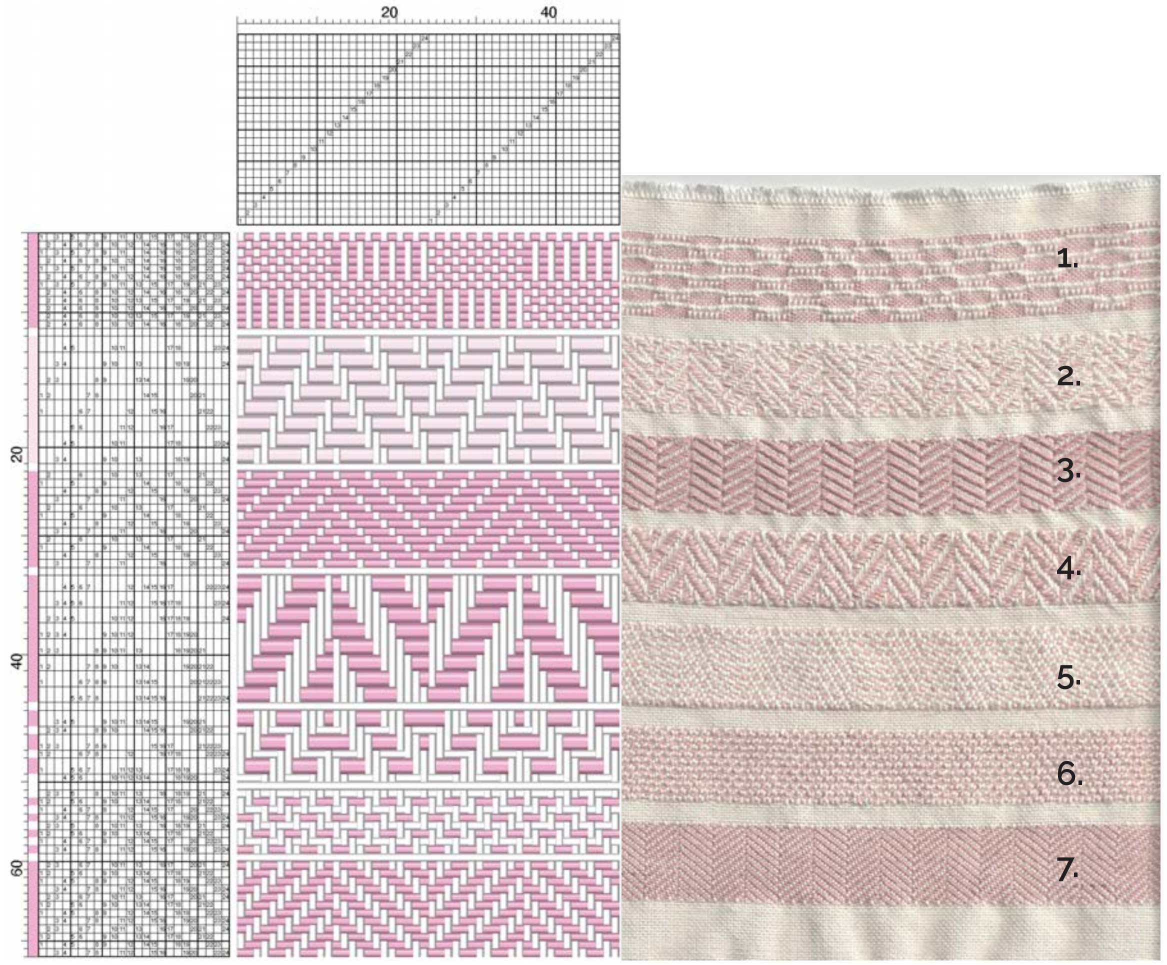


Figure 87: Computerised weaving draft for test strips and woven test strips.

Seven 1-inch strips with various colour combinations, patterns, and textures were woven into a single fabric piece to generate multiple swatches. HAG and I then discussed our preferred swatches based on design, explicitly selecting variations in features and handles to assess their performance on a larger scale.

HAG noted that, like the knitting trials, the fibres tended to shed heavily during weaving despite their silk-like texture. This shedding could impact the overall quality of larger pieces as the warp undergoes more strain.

It was predicted that tighter woven materials might experience snags in areas where the warp is subjected to increased stress.

Numbers 2, 4, and 5 were chosen for further development among the swatches. These swatches offered the most significant variation in weight, pattern, and structure, providing ample opportunities for exploring multiple colour options.

Results: When dying yarns for the final range of samples, HAG noted that:

"The yarn dyes easily, taking colour well and absorbing quickly. The yarn did not become overly tangled or difficult to manage, even when agitated, similar to silk and unlike wool. The dyed yarn became stiff and smooth once dried but soon became supple after winding. No obvious damage/degradation caused by dyeing." (HAG)

Regarding the final samples, the materials exhibited an overall soft and lustrous handle reminiscent of modal wool or silk wool blends. As with the previous samples, they possessed a silky sheen and presented a luxurious appearance, particularly in the flatter, pressed samples such as samples 6 and 2.

As anticipated, some visible signs of snagging were observed where the yarns had shed or frayed. This was particularly noticeable in the tightly woven sample 1, the first to be woven. Consequently, samples 2-6 were woven with slightly looser tension to reduce strain on the yarn. Notably, samples 4 and 6, woven with single-pick lace weight yarns, exhibited the cleanest finish with minimal signs of fraying.

Sample 1:
3 yarns used: Pick and pick, Bulky weight yarn: 2. A, 2. B & 3.
Structure 2.
Fringing using bulky weight yarn created on edges.
Pressed.


Figure 88: Sample 1 - Final range of commercially woven samples

Sample 2:
1 yarn used: Single pick, Laceweight yarn: 1. B.
Structure 4.
Small herringbone design. Some difficulties with yarn breaking throughout.
Pressed.


Figure 89: Sample 2 - Final range of commercially woven samples

Sample 3:
4 yarns used: Pick and pick, Bulky weight yarn: 2. A & 3, 2. B & 1. A.
Structure 5 occasionally reversed. Left un-pressed for loftier texture.


Figure 90: Sample 3 - Final range of commercially woven samples

Sample 4:
1 yarn used: Single pick, Lace weight yarn: 1.D.
Structure 6.
Keracol dyed yarn.
Pressed


Figure 91: Sample 4 - Final range of commercially woven samples

Sample 5:
3 yarns used: Pick and pick,
Bulky weight yarn: 2. B,
Laceweight yarn 1. C & 3.
Structure 7.
Pressed


Figure 92: Sample 5 - Final range of commercially woven samples

Sample 6:
2 yarns used: Single pick,
Laceweight yarn 1. C. Yarn 3.
Structure 8, occasionally reversed.
Pressed


Figure 93: Sample 6 - Final range of commercially woven samples

In her final comments, HAG highlighted the following:

"The yarn is easy to work with, has a luxurious handle and creates lovely fabrics. Attention must be paid to handling and equipment setup to avoid excess friction being placed on the yarn. However, with these mitigations in place, the yarn is easy to work with."

"The yarn is prone to shed fibres, but this can be controlled by reducing friction. The yarn also takes dye beautifully. However, my next concern would be to see how the fabric performs in a rub testing. Given the problems weaving with high tension, I would expect these fabrics to perform poorly in rub testing; they are likely to weaken quickly or produce pilling/shed fibres." (HAG)

Reflection: Generally, the samples had a beautiful handle. They were soft and silky in texture with a nice weight, suitable for a lightweight coat fabric. The soft colours created a summery colour pallette when woven in with the undyed, cream-coloured yarns. Some samples featured fringing, representing an alternative method of finishing. This fringing could be trimmed to the desired length and used on a garment's bottom hem or sleeves.

The range of samples successfully achieved a variety of weights and finishes. The materials felt soft and breathable against the skin, eliminating the need for a lining and maintaining a light and airy feel to potential garments.

Samples 1, 3, and 5, all featuring bulky weight yarn, were the heaviest and most complex weaves. While these samples showcased high decorative appeal, from an end-of-life perspective, it is presumed that they would take longer to degrade than samples made from lighter-weight yarns. Moreover, in terms of the energy and time invested in their production, these intricate weaves would entail higher costs and resource consumption.

Some samples exhibited more snagging and fraying than others, which could be a potential concern from a traditional textile quality perspective. However, an opportunity exists to consider this within a short garment lifecycle, where durability is less regarded. These considerations exemplify the design decisions required within a regenerative design framework. Factors such as the desired lifespan of the garment, material quality, degradation, and the resources invested in manufacturing must be carefully balanced.

5.3.10 Applying The Outcomes Of Knowledge Integration: Ex 4-12

The preceding investigation emphasises the significance of knowledge integration and collaboration in material experimentation, drawing on specific examples from textile dyeing, colouration, and construction techniques. By analysing the insights gained through collaborative efforts, this section underscores the profound impact of knowledge Integration on enhancing research outcomes and advancing the understanding of the application of chemistry within design processes (and vice versa).

The findings highlighted the critical role of collaboration in addressing industry-wide challenges, such as lab-scale material development and optimisation of dyeing processes, whilst demonstrating the value of expert feedback and evaluation, contributing to informed decision-making and alternative design methods. By sharing experiences and insights, researchers have fostered a deeper understanding of the properties and behaviour of casein materials by incorporating external expertise from different disciplinary backgrounds.

The knowledge acquired through this practice-based investigation was fed back to JH in the lab. Although there was limited cross-over to the information obtained through weaving and work done in the lab, the continued dialogue and interest between researchers' areas of expertise helped spark ideas and areas of creativity further down the line. This is particularly evident in Chapters 7 and 8, throughout the evaluation of the transdisciplinary methodology and the potential of future research projects.

5.4 From Lab To Loom: Development Of Casein Filaments

This section delves into the laboratory work conducted by JH and I, which spanned from October 2019 to March 2023. It comprises four main experiments investigating the development and use of casein mono-filaments suitable for weaving. Ex 13, 14 and 15 are centred around a three-day lab visit to UoL, where I worked closely with JH to experience the wet-spinning process first-hand and replicate tests for myself. These sections were documented based on shared lab reports, photography, and note-taking, while the reflection drew upon collective discussions and contemplation.

The research conducted at UoL was organised in the following way:

Day 1: Two batches of casein dope were prepared – one for regular spinning trials and one for dope dyeing. JH demonstrated the ESR with the opportunity to run some practice spinning trials using a pre-prepared casein dope (5.4.1/5.5.2).

Day 2: First trial of wet spinning in colour – Dye to be tested in 3 different ways: directly in the dope, hardening, and wash bath (5.4.3).

Day 3: Assessment of dried fibres and material testing: Tensile testing of dyed and undyed yarns (5.5.1).

Ex 15 involved knowledge from experiments 3 and 7, which was leveraged to develop a process for wet-spun dyeing of casein. This served as an opportunity to explore the hypotheses outlined in section 5.2.3 regarding the dope dyeing and wet spun (In-situ) dyeing of casein filaments to achieve more reliable and consistent colour whilst potentially enhancing material properties such as strength. BCP provided by Keracol was used for these experiments.

Ex 16 focused on designing a small woven range of samples using lab-produced casein filaments, with continuous feedback and ideas shared among JH, HAG, and I.

Learning Process

The learning process for this research section adopted an iterative approach, combining literature review, replication, conversation, and documentation to explore new collaborative ways of working in the lab. The development of casein filaments built upon previous work with casein films, incorporating historical data from patents and journals to establish a standard methodology. Regular online meetings between JH and I facilitated discussions on trial results, enabling me to understand the fundamental procedures and techniques despite not being able to replicate filament production domestically.

The development of coloured casein filaments also drew upon my own work with coloured casein films domestically and their lab placement at Keracol. Collaborative assessments involving JH, AT, RB, and myself were conducted from a chemistry perspective to address challenges encountered during the lab placement, particularly regarding colour stability using anthocyanins with a low pH. The insights gained influenced the development of a new colouration process, allowing the dye to bond with the fibres during the wet spinning process.

5.4.1 Ex 13: Experimental Spinning Rig

Aim: This research explores the early challenges encountered during the development of the ESR and the iterative testing of spinning equipment and methods. The study aims to provide a comprehensive understanding of the spinning process and gain insights into the methods used for fibre development in the lab. Additionally, it seeks to identify and address the challenges associated with wet spinning at this level and how these might be overcome.

Location: Laboratory (UoL)
Collaborators: JH
Tools/Materials: Casein (powder), NaOH, Deionized water, beakers, measuring scales, magnetic stirrer, tweezers, ESR.

Method: JH conducted an initial demonstration of the ESR. During this time, the drying element of the rig still needed to be completed, leading to the exploration of alternative methods for winding and drying the filaments. The casein dope was prepared using the following basic formula:

Casein Dope Formula:

- Casein: 24wt% (48g)
- Sodium Hydroxide: 25wt% stock solution (NaOH = 1.5wt% from 12g stock solution)
- Deionised water: 140g

Casein Dope Preparation:

- Hydration of 48g (24wt%) casein powder in 140g of distilled water by stirring at 500rpm for 2 hours in a sealed container.
- Add 12g of 25wt% NaOH solution to the container, stirring at 140rpm for 4 hours.
- Age the dope by leaving the container sealed for 16 hours, ensuring complete hydration of the casein powder and thoroughly blending all components.

Spinning Procedure: Figure 94 illustrates the basic components of the ESR developed by JH. Before spinning, preparation of the coagulation bath (B1), hardening bath (B2), and wash bath (B3) was necessary. For the coagulation and hardening baths, 120g of $MgSO_4$ (magnesium sulphate) and 120g of $Na2SO_4$ (sodium sulphate) were dissolved in 600g of distilled water. Additionally, 100g of concentrated $H2SO_4$ (sulphuric acid) was added dropwise to the solution while stirring continuously. Finally, the wash bath required 500ml of distilled water.

The spinning process begins at the top left of the diagram, where the casein dope is pumped (PA) at 1ml per minute until the first filament is extruded through the spinneret (SP). Subsequently, the flow rate is reduced to 0.5ml per minute, and the spinneret is immersed in the coagulation bath.

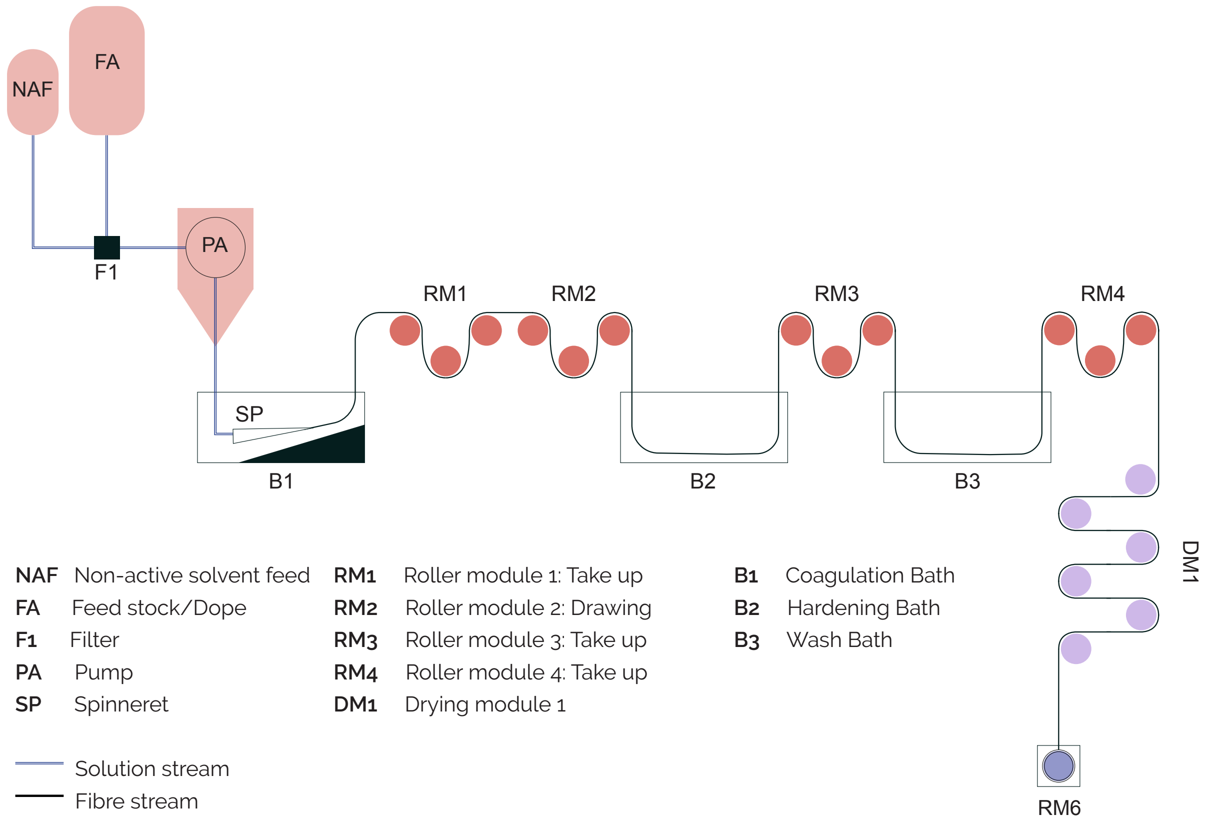
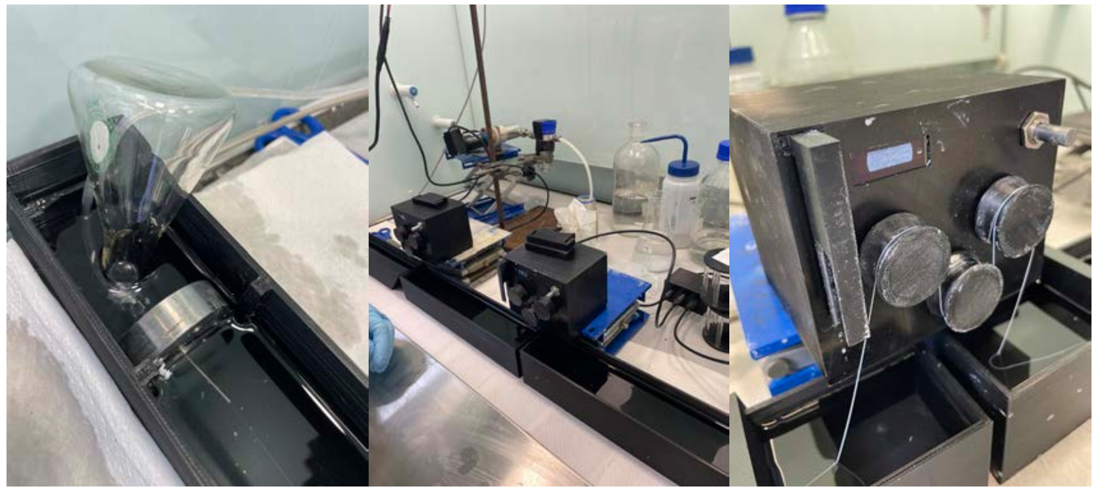


Figure 94: Wet spinning process using the experimental spinning rig.

The extruded fibre (represented by the black line) is hand-guided through the coagulation bath onto the take-up rollers using tweezers. Initially, the rig was configured to produce monofilament using a 21G needle at 0.2ml/min and a take-up velocity of between 0.1m/min and 2.32m/min. After several initial demonstrations by JH, the take-up speed was set to 1.5m/min.

The hardened fibre remains in the hardening bath for 5 minutes before being transferred to the wash bath, where it is soaked for an additional 1 minute. The drying roller modules and final

take-up rollers were unavailable at this stage, necessitating the filament's manual winding onto glass tubing for air drying. This process proved challenging as the wet filaments were delicate and prone to breakage. Moreover, this drying method increased the filaments' brittleness once dried.



Figures 95-97: Dope is extruded from the needle into a fine filament, travelling through the coagulation fluid. This filament is taken onto the first set of rollers using a pair of tweezers.

Results: The initial demonstrations conducted by JH revealed the difficulties encountered when working with filaments in this manner. Manual guidance of the filament from the coagulation bath to the take-up rollers required constant attention to ensure smooth passage through the system. Additionally, air bubbles in the pump caused issues by forming globules within the filament. Due to the fragile nature of the wet filament, these globules further contributed to filament breakage when passing through the rollers.

Increasing the take-up speed to 1.5m/min partially alleviated some of these issues. This speed enhancement stretched the filament into a thinner strand as it traversed the system, resulting in a finer, softer, and more flexible filament. Although achieving a smooth filament flow through the system remained challenging, using the rig in this state enabled the production of filament quantities sufficient for visual and physical exploration of variations in take-up speed, dope constituents, and dyeing methods, signifying a significant accomplishment.

While the ESR was still in the development stage, several issues with the final filaments arose due to mechanical factors of the rig and difficulties in achieving consistency in the casein dope. However, most of these issues were resolved upon completion of the rig and implementation of the final drying system. These challenges and their subsequent resolutions are discussed in detail in the upcoming section (5.4.2), accompanied by an analysis of the obstacles that were overcome.

Reflection: The initial demonstrations conducted by JH highlighted the inherent difficulties in working with filaments using the developed ESR. The manual guidance of the filament from the coagulation bath to the take-up rollers required constant attention to ensure its smooth passage through the system. The presence of air bubbles within the pump exacerbated the issue by creating globules within the filament, leading to its breakage when passing through the rollers. These challenges highlighted the fragile nature of the wet filament.

However, an improvement was observed when the take-up speed was increased to 1.5 meters per minute. This adjustment stretched the filament, resulting in a thinner, finer, and more flexible strand. Despite the ongoing challenges in smoothly operating the filament through the system, using the rig in this state still enabled the spinning of filament in sufficient quantities to visibly and physically explore the variations in take-up speed, dope constituents, and final material, marking a significant achievement.

While the ESR was still undergoing development, mechanical factors of the rig and difficulties in achieving consistency in the casein dope posed challenges in producing the final filaments. However, many of these issues were successfully overcome once the rig was completed and the final drying system was implemented. In the next section, these challenges and their resolution are discussed and analysed in detail.

Overall, the previous experience provided a valuable learning opportunity to understand the challenges associated with wet spinning alongside the historical challenges faced when working with casein as a raw material.

5.4.2 Ex 14: Casein Filaments: Lab Results

Aim: This section documents the utilisation of practice as a method of knowledge integration between design and chemistry disciplines. The focus is on developing lab-based casein filaments, with a detailed outline of the methodology employed. The study analyses the results from both design and chemistry perspectives, considering the properties and feasibility of the casein filaments. The overarching goal of this exercise is to create a non-toxic, compostable casein filament that meets the requirements of the vision as described in Section 4.3.

Location: Laboratory (UoL)
Collaborators: JH
Tools/Materials: Casein (powder), NaOH, Deionized water, beakers, measuring scales, magnetic stirrer, tweezers, ESR.

Method: The casein dope preparation outlined in Section 5.2.2 (p119) served as the foundation for the tests conducted in this study. Using the process outlined in Section 5.4.1 (p171), trials were run continuously throughout the afternoon to develop enough filament for assessment.

Results: One issue was the blebbing of filaments (protrusions on the fibre), which created weak points in the filaments, causing breakages. This was improved by implementing a more rigorous and lengthier steady-state step in the spin. The dope needed to be extruded through the pump and spinneret for at least an hour at the intended flow rate for the system to become a 'steady state,' resulting in uniform flow and consistency.

Another issue came from the spinning methods. If spinning is stopped mid-process, the dope coagulates (hardens) in the needle and requires a much higher flow rate initially to 'break' through the hardened dope. Although the flow rate can be reduced once the blockage has been punctured, the needle often requires replacing and unblocking manually via thermal degradation of the solidified polymer. It is, therefore, imperative to always keep the flow through the needle during immersion in the coagulation bath.

The filaments produced at this stage were also very brittle and sometimes snapped upon removal from the drying utensils or take-up rollers. This was primarily due to uneven stretching of the fibres as they were manually wound onto the drying utensil, causing points of non-uniformity that were weakened. A take-up roller was used to dry the filaments in the early stages. Using this method, there was less control over the separation of filaments, which then tended to overlap.

Whilst the filament is wet, it is still porous and very soft. This means that if the material is wound onto itself under tension (as in the take-up module), it deforms and sticks to the other fibres being wound, causing them to bond, which increases brittleness. This was temporarily solved by switching to a manual drying system by hand-winding the filaments onto glass cylinders, ensuring they did not overlap and allowing the filament to dry more evenly. Later in the project, the inclusion of a drying module vastly improved the quality of dried filaments by ensuring the material was adequately dried and, therefore, not as 'soft' before winding onto the final spool.

Figures 98-100: Preparation of casein dope for extrusion. The dope is thick yet pourable.

The fragility of the filaments was also an area for further development. Coming from a textile background and having worked with commercial casein fibres, I initially found it challenging to understand the reasons for the differences in feel and structure between the fibres and filaments. The commercial casein fibres were very soft and fluffy, whereas the filament produced so far resembled more of fishing wire or horsehair.

This was due to several reasons. Firstly, the needle used for spinning filaments was 21G. This is very thick for spinning fibres; however, it is challenging to spin fibres thinner than this at lab-scale due to the need to manipulate them through the rig manually. Any needle size smaller than 21G makes the fibre almost impossible to see with the naked eye; therefore, this would not be possible. As the filaments are thicker, they are less ductile and have less drape. The filaments produced in the lab are also monofilaments. These tend to be more brittle and weaker than yarn. When used commercially, monofilaments would be cut into staple lengths and spun into a yarn, increasing the tensile properties and drape.

Post-Drying System

Once the drying modules and final take-up rollers were complete and added to the ESR, the quality of the fibres improved dramatically. A combined drying and drawing rig has been developed, which simultaneously dries the filament and draws it up to a factor of 3.5x. Drying and drawing the filaments simultaniously, which are crucial steps in the wet spinning process, allows the filament to be wound straight onto a spool without sticking to itself. Drawing also increases the material's tensile properties by aligning the individual molecules within the fibre to increase chemical interaction and strength. This also tends to make the filament finer and with a more uniform cross-section, which increases flexibility and drape.

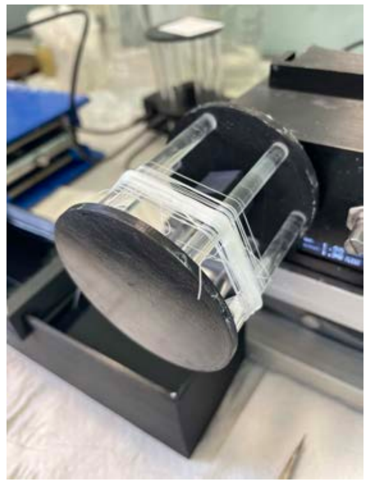


Figure 101: Hand winding of casein fibres onto various utensils for drying.
Figure 102: Winding of casein filaments onto make-shift takeup roller (awaiting final drying system).
Figure 103: Results of dried monofilaments without final drying system - filaments stick together and become very brittle.

Regarding the spinning process, having a final drying system in place also allowed JH to spin far larger quantities (upwards of 5km a day). This is because the filament no longer required manually winding onto a drying utensil, which was time-consuming and limited the amount of fibre in proportion to the size of the glass cylinder. The spin would also often have to be paused to do this. Eliminating this stage makes the spinning process more practical and streamlined.

The steady stage section of the rig was also improved to solve the issue of blebbing. Clips were added to the rig to hold the fibre under the coagulation fluid's surface for the entire bath length. This ensures that the filament is extruded from the spinneret more gently and evenly so as not to cause a dragging effect, which can alter the cross-sectional morphology of the fibre.

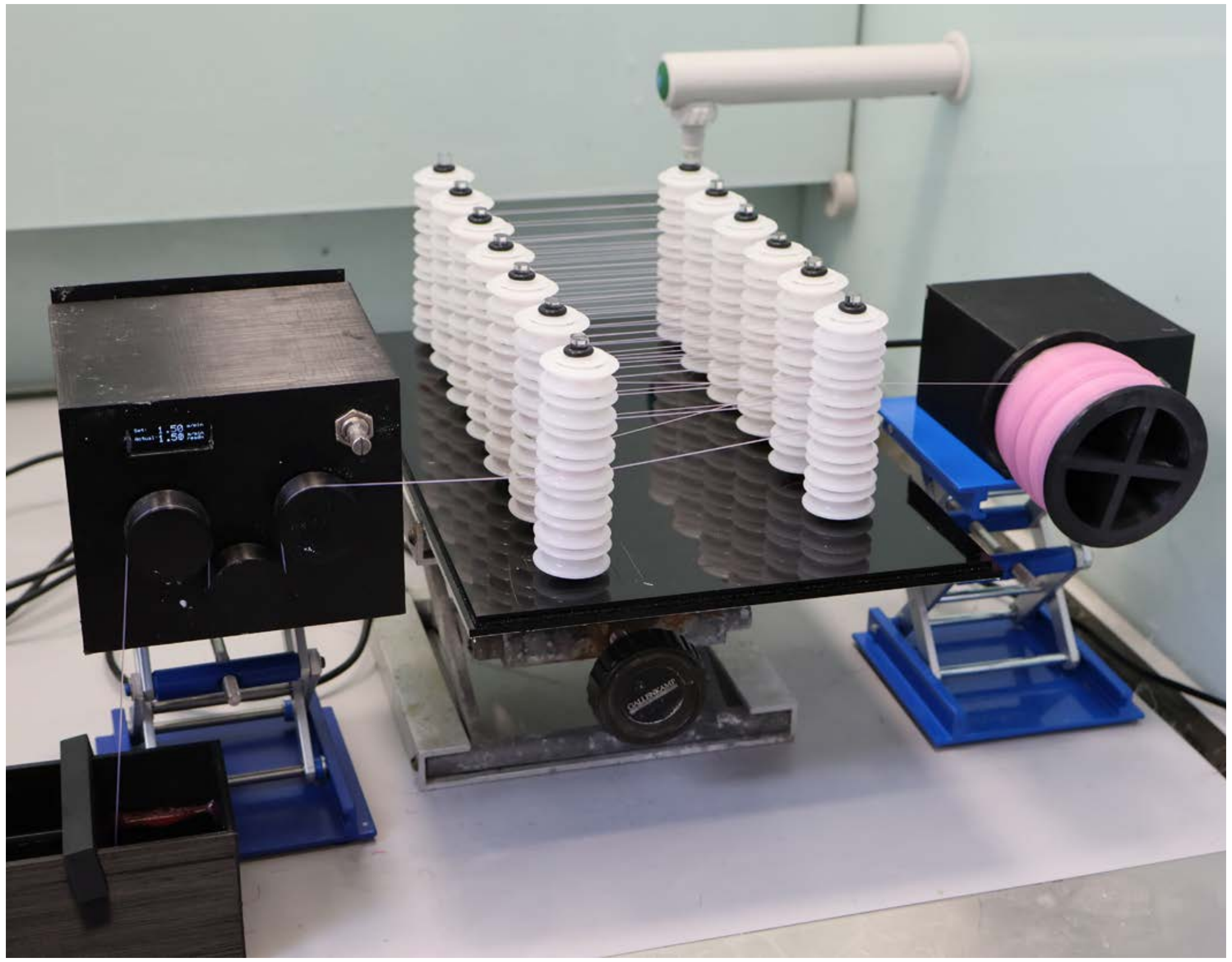
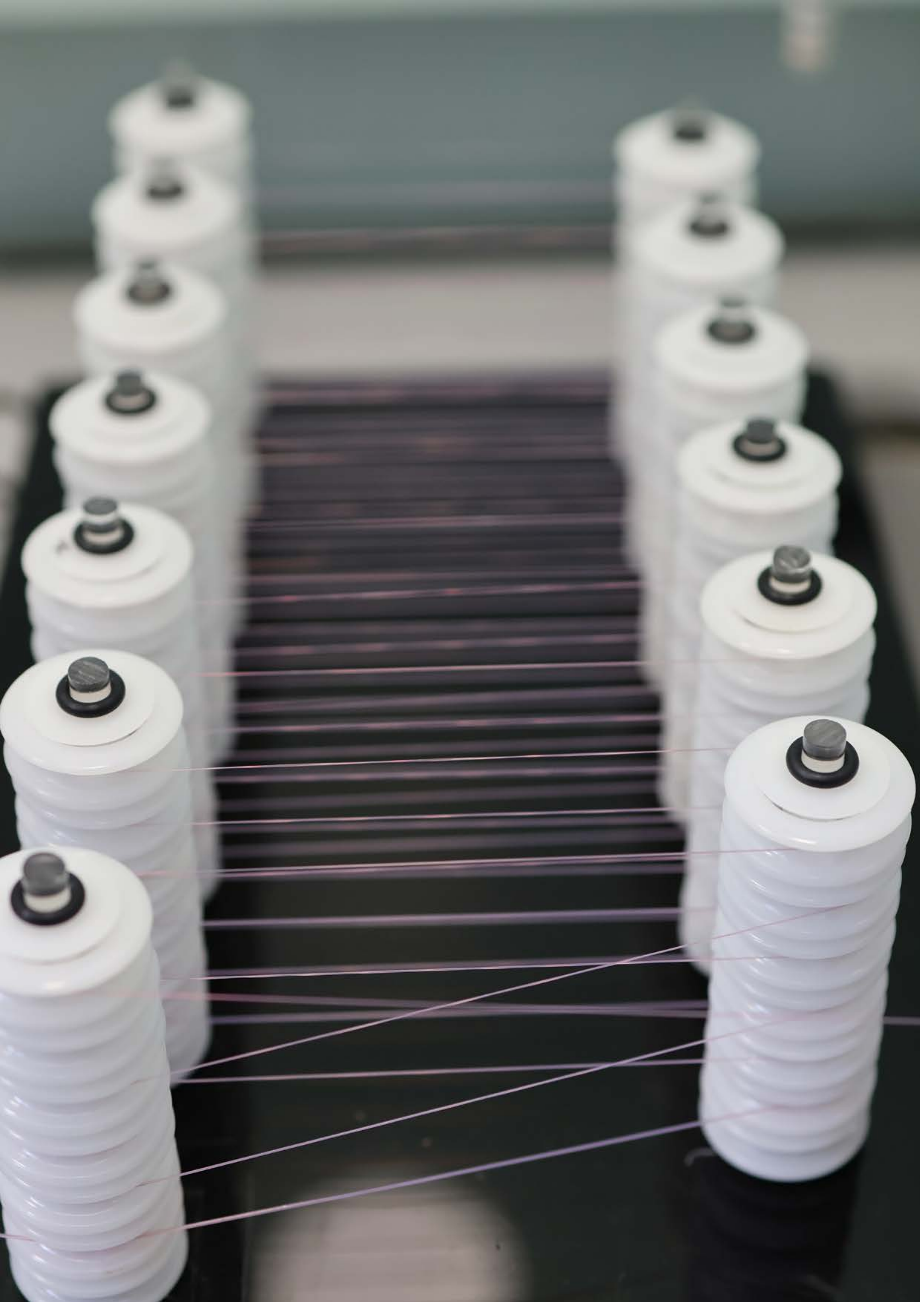


Figure 104: ESR complete with final drying system and takeup roller (photo by JH).



Reflection: The challenges highlighted the importance of addressing issues in the filament production process to improve the quality and reliability of the final product. Further refinement of the spinning and drying methods is still necessary to produce filaments that are less brittle and have better tensile properties. The challenges also underscore the need for careful design considerations to optimise the spinning rig and ensure uniform filament production.

The knowledge gained from addressing these challenges has significantly improved material quality. Implementing a combined drying and drawing rig and adjustments in the spinning process has resulted in higher-quality filaments. Drawing the filaments has enhanced their tensile properties, alignment, and uniformity, improving material quality. These changes have made producing finer, more pliable filaments and more uniform cross-sections possible.

To make these filaments suitable for weaving, further developments are necessary. While the improvements made so far have enhanced the quality of the filaments, additional steps may include exploring ways to reduce filament thickness, possibly by using thinner needles, while maintaining visibility and manageability at the lab scale. Additionally, considering the transition from monofilaments to fibres and the creation of yarns may be necessary to increase tensile properties and drape.

5.4.3 Ex 15: Development Of Coloured Filament

Aim: This research aims to investigate and evaluate the potential of wet-spun dyeing for casein filaments using BCP (provided by Keracol), assessing colourfastness, colour stability, and the potential environmental advantages of incorporating dyes at various stages of wet spinning.

This research section was designed in response to previous experiments conducted with BCP dyes, aiming to address the challenges of achieving consistent and robust colours. It was hypothesised that colour changes resulted from dye contamination on the fabric's surface due to other substances or altered pH levels. If this hypothesis is correct, dyeing the filament in its wet state before drying would facilitate better dye penetration, thereby preserving the colour deep within the filament.

Location: Laboratory (UoL)
Collaborators: JH, Keracol
Tools/Materials: Casein (powder), BCP, NaOH, Deionized water, beakers, measuring scales, magnetic stirrer, tweezers, ESR.

Method: JH and I collaboratively conducted four initial colour tests during my lab visit at UoL. The casein dope formula outlined in section 5.4.1 was utilised for these tests, except for test 2, which required a lower weight percentage (wt%) of casein. The dope preparation method described in section 5.4.1 (p171) was followed for each test.

Figure 105: Final dyring system for the ESR - drying of in-situ dyed casein filaments (photo by JH).

For tests 1 and 2, BCP was added to the dope and the NaOH solution and mixed for four hours before being sealed and matured for 16 hours. For tests 3 and 4, a regular casein dope was used, and BCP was added directly, either to the hardening bath or wash bath. The ESR was set at a flow rate of 0.2ml per minute, with a take-up velocity ranging between 0.5 and 1.0 meters per minute.

Test no	Test type	%BCP	%Casein	Timings
1	Dope dye	0.5wt% of dope (1g)	24% (48g)	-
2	Dope dye	0.1wt% (0.2g) of dope	20% (40g)	-
3	In-situ dye: coagulation bath dye	1wt% of bath (1g)	24% (48g)	Left in dye bath for 10 minutes, washed for 10 minutes.
4	In-situ dye: Wash bath dye	1wt% of bath (0.5g)	24% (48g)	Left in dye bath for 10 mins, washes for 10 minutes.

Table 23: Dye test type and method (tests 1-4).

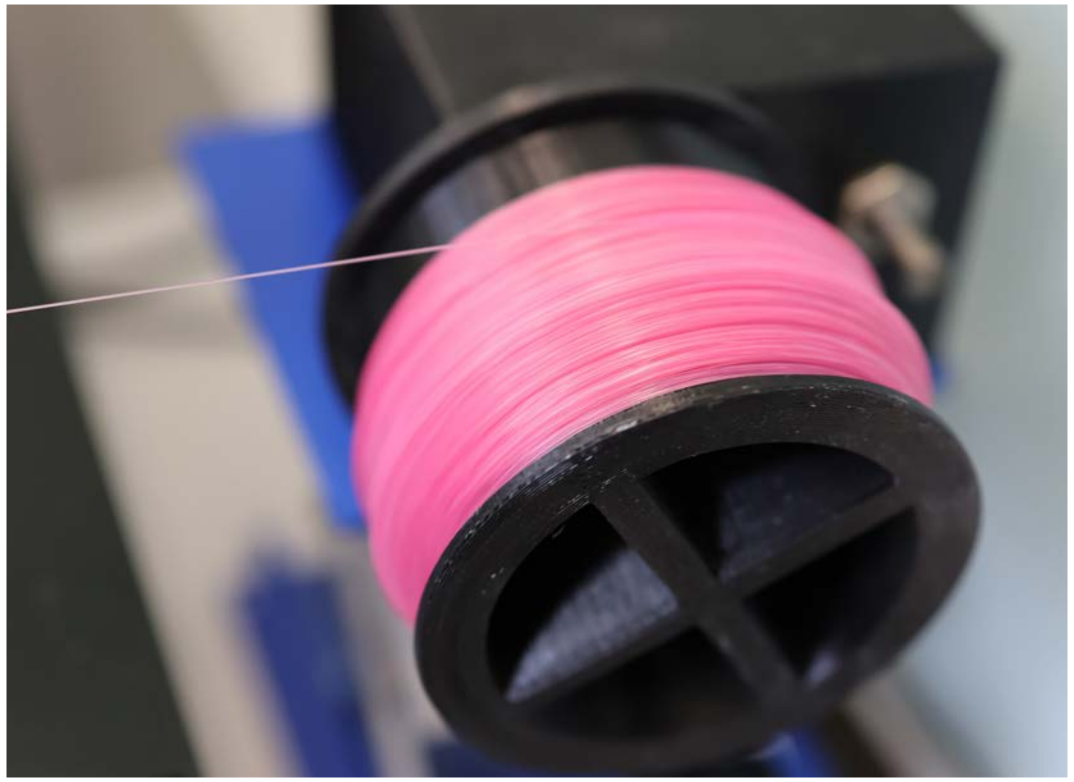


Figure 106: In-situ BCP dyed filament wount onto final takeup roller (photo by JH).

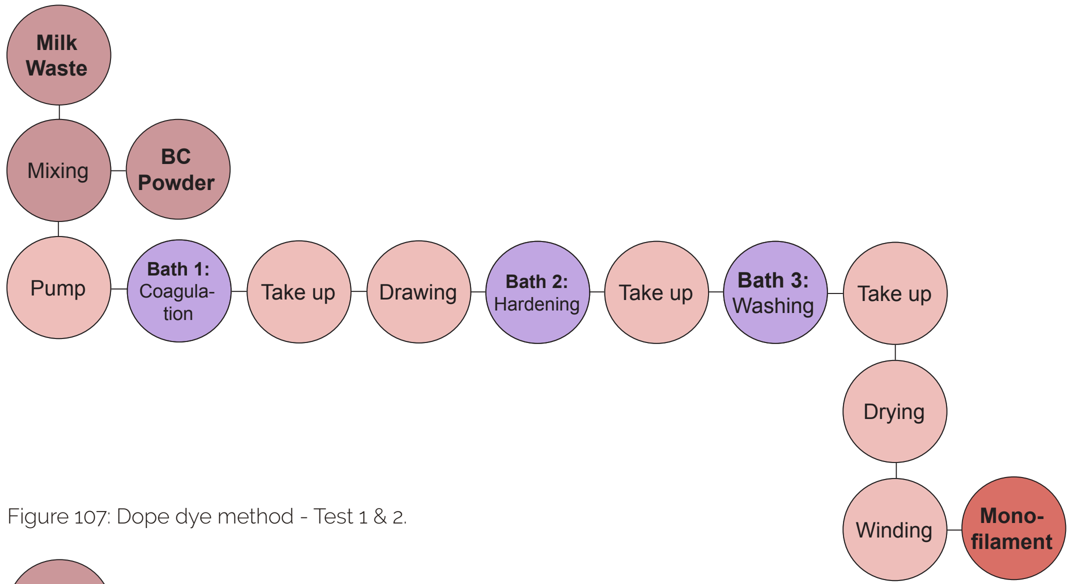


Figure 107: Dope dye method - Test 1 & 2.

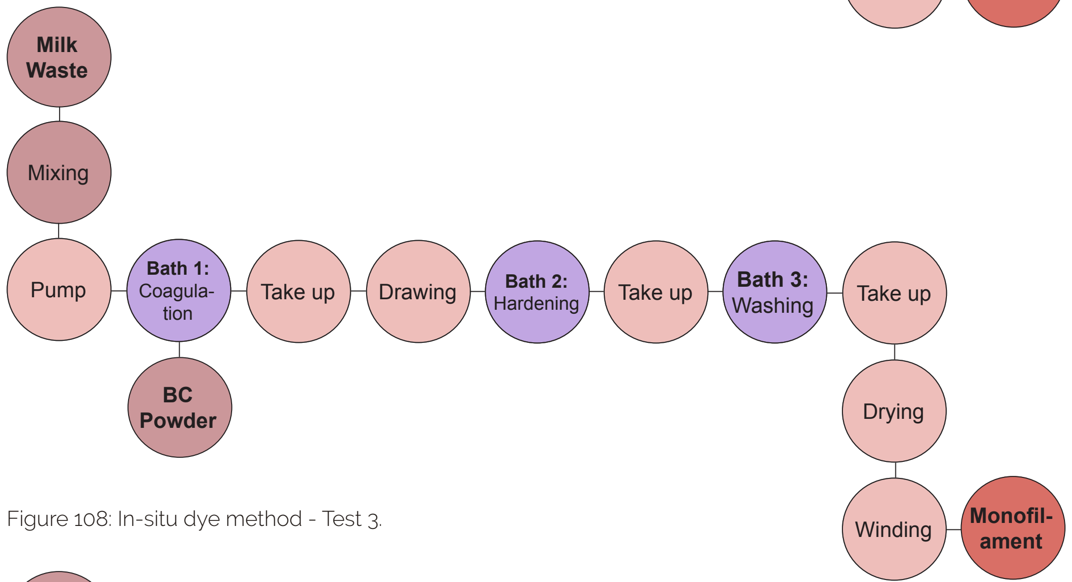


Figure 108: In-situ dye method - Test 3.

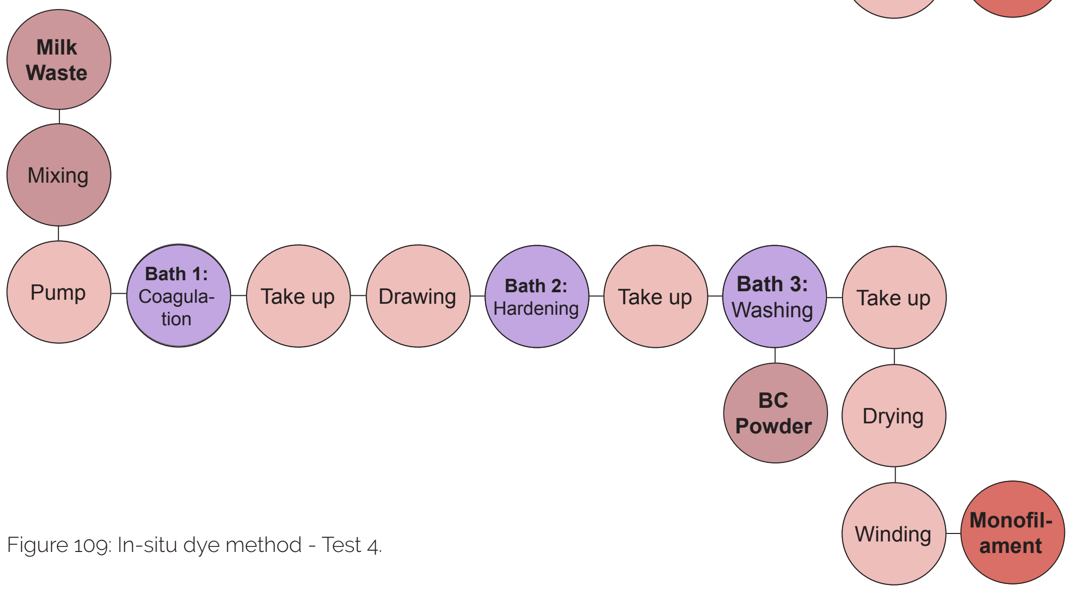


Figure 109: In-situ dye method - Test 4.

Test 1 Results: During the dope preparation, mixing the BCP proved challenging due to the thick consistency of the casein dope. Despite continued mixing, the dope thickened over time and turned a dark brown colour after 16 hours of maturation. This high viscosity hindered extrusion through the fine needle, and the dope had to be disposed of.

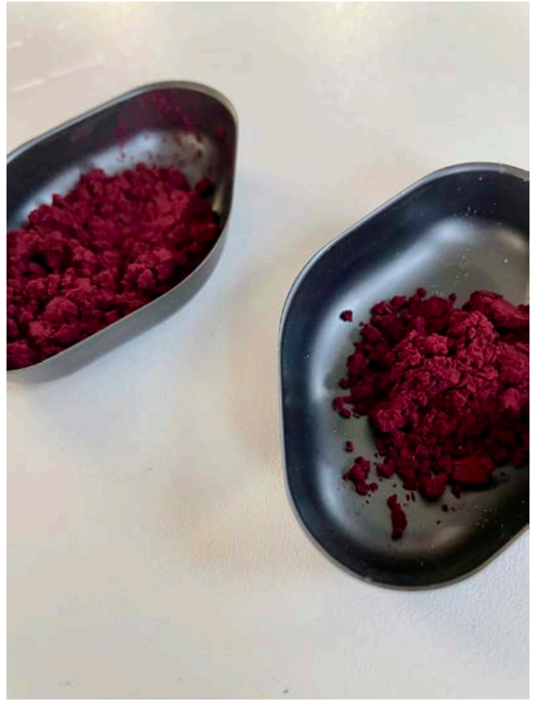


Figure 110: In-situ dye test 1 - Meausing of BCP.

Figure 111: In-situ dye test 1 - Adding BCP to casein dope.

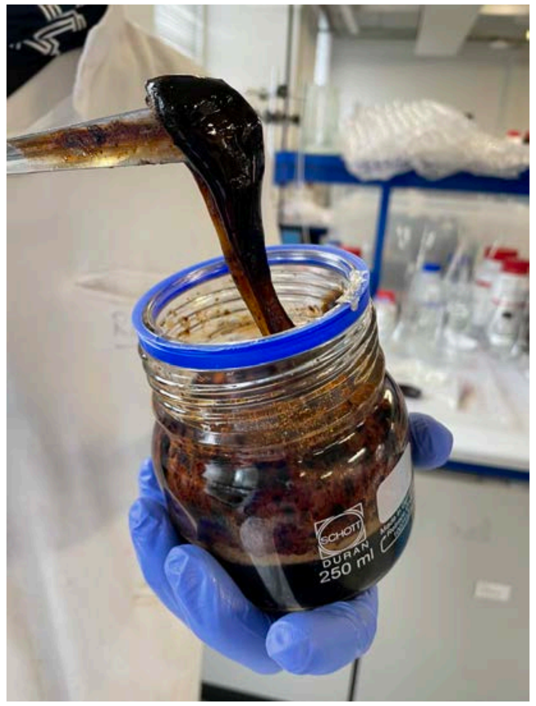
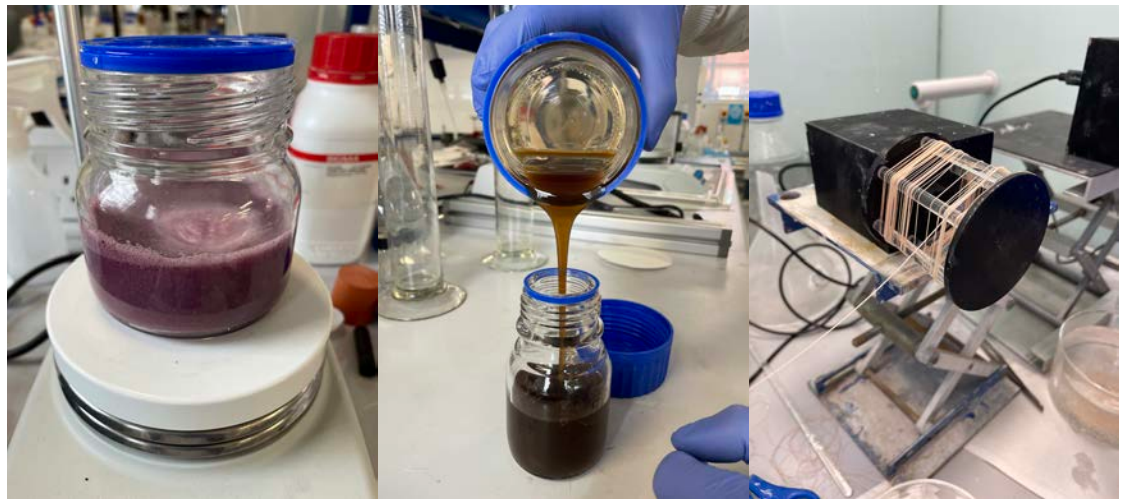


Figure 112: In-situ dye test 1 - Testing viscosity.

Test 2: Results

Based on the findings from test 1, the dye weight was reduced to 0.1% (0.2g) and dissolved in 140g of water before being added to the dope. The casein weight was also decreased to 20% to lower the overall dope viscosity. The resulting dope appeared to have a much more suitable viscosity and a strong purple colour. After sitting for 16 hours, this colour again turned to a dark brown, demonstrating the degradation of anthocyanins (most likely due to the higher pH of the casein dope).



Figures 113 - 115: In-situ dye test 2 - preparation of dope and spinning of monofilament,

However, the dope's thickness and viscosity remained much more suitable for use, and so was tested with the hope that the colour would appear different once extruded. The filament ran through the rig well with little difference in strength or thickness to the undyed filament. Interestingly, once extruded, the filament had only a pale pink/nude colour in contrast to the dark brown of the dope. This colour did not appear to be affected by the coagulation or hardening bath solution and ran consistently through the ESR.

Once dried, the colour of the filament changed dramatically to bright orange. This was an unexpected result due to the BCPs colour and the dope's dark brown pigment. This colour change is most likely due to the shrinking of the filament as it dries, meaning that the colour appears more intense as it becomes more concentrated within the filament. Whilst unintended, the soft colour of the filament was quite pleasing and remained stable over time, showing promise in the method overall.

The texture of the filament resembled that of fishing wire or horsehair. It was soft, lightweight, and flexible with a silky, lustrous sheen. In terms of strength, the filament was very fine and snapped easily under pressure. In its current state, it would not be suitable for weaving or use in any form of textile construction.

Figure 116-117: Test 1 and 2 - BCP is added directly to the casein dope.

Test 3 results: In this test, undyed casein dope was extruded and introduced directly to the dye in the hardening bath. The filament underwent a series of processes, including passing through the ESR, the hardening/dye bath, a roller module, and a wash bath. The filament absorbed only a minimal amount of colour, resulting in a pale pink/cream colour. Washing revealed some dye runoff, and the dried filament was a soft pink with a wiry texture.

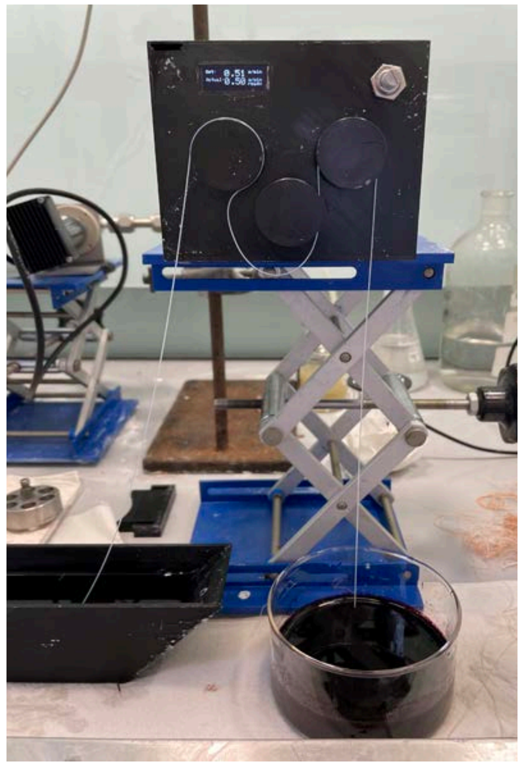


Figure 118: In situ dye test 3 - Filament passing through the ESR and into a dye filled hardening bath.

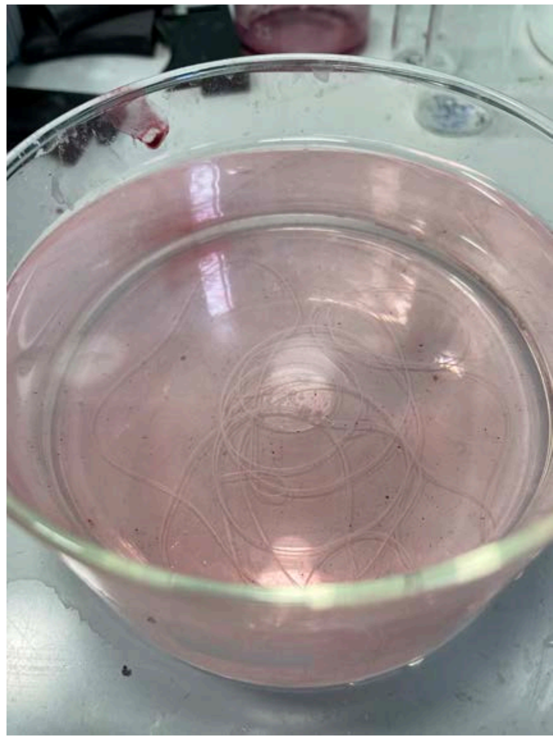


Figure 119: In-situ dye test 3 - wash bath.

Figure 120: In-situ dye test 3 - filament results.

Test 4 results: The final test explored adding colour at the end of the spinning process through the wash bath. BCP was added directly to the wash bath, where the wet filament soaked before being transferred to a second wash bath. The filament retained a vivid shade of pink throughout the drying process, developing into a deeper hue. The texture of the filament remained unaffected by the dye.

Figure 121: In-situ dye test 4 - filament in wash bath.

Figure 122: Hand wound filaments onto glass viles.

Figure 123: In-situ dye test 4 - filament results.

Overall, these initial colour tests provided insights into the dyeing process for casein filaments. Various methods of dye incorporation yielded different results in colour absorption, colour retention, and colour development. The findings suggest the potential for achieving a range of colours by introducing dyes at various stages of the wet-spinning process. The texture of the filaments exhibited qualities similar to fishing wire or horsehair (which are common properties for mono-filaments), but further improvements are needed to enhance their strength for suitability in weaving or textile construction.

Reflection: The results of the four dye tests conducted in this study have provided an interesting and exciting range of outcomes from a design perspective. Initially, test 2, which involved combining the dye directly with the dope, appeared unsuccessful due to the brown colour of the resulting dope. However, upon extrusion, the filament exhibited surprising colours. While the expected shade was not achieved, the presence of pigment indicates promising potential, as the dope did not fully degrade the anthocyanins.

Introducing the dye at different stages of the wet-spinning process proved highly successful and allowed a wide range of colour shades. Minimal to no colour runoff and colourfastness were observed in the resulting filaments. In contrast to previous tests exploring methods of surface dyeing (Ex 6 & 7), the filaments did not change colour upon contact with water. This suggests that even when the dye is added during the later stages of wet spinning, it can penetrate the filament more deeply than traditional surface dyeing methods.

These encouraging initial results pave the way for further research in wet-spun dyeing for casein filaments. The ability to achieve a diverse range of colour shades using the same dye simply by adjusting the stage of dye incorporation during the wet-spinning process opens significant opportunities for further exploration in this field.

Figure 124: Comparison of colour between in-situ dye tests 3-4.

The wet filaments' porous and swollen state allows them to absorb the dye like a sponge until they are drawn and thoroughly dried. Adding any chemical at this wet stage, such as a cross-linking agent, plasticiser, or dye, enhances filament penetration, enabling the dye to bind to the protein molecules both on the surface and within the cross section of the fibre.

From a commercial and environmental perspective, incorporating dye into the spinning process offers significant advantages. It reduces water usage for fabric colouring, particularly in the case of dope dyeing. Furthermore, it could eliminate an entire stage in the textile processing or garment design process further down the production line, thereby reducing water and energy consumption and eliminating toxic waste.

Continued Testing

Through this project, the design of the ESR had taken precedence over the development of casein filaments and, at this point in the research, was still under development. Although this lab visit served as a valuable experience and an initial insight into the possible methods of wet-spun dyeing, we still could not achieve the desired filament quality to be taken forward for textile production.

In terms of continuing with this research, the drying system needed to be in place to begin to assess the filaments (both dyed and undyed) in terms of textile quality. This would involve exploring various cross-linking agents, conducting tensile testing, wash-fastness testing compostability testing, and testing on the loom.

Due to time limitations, JH could only pursue one method of wet-spun dyeing. Test 4 was the most successful because it produced the strongest, most vivid colour. Due to previous difficulties surrounding pH and colour change, the initial stage of continued research aimed to determine the maximum temperature and pH the filament could withstand without degrading. Three variables were tested (dyeing time, bath temperature and bath pH) with three levels of each variable:

Dyeing Time (minutes)	Bath Temperature (˚C)	Bath pH
2	30	2
10	50	4
30	70	6

Table 24: Variables for ongoing experimentation of wet spun dyed casein filaments.

The second stage of continued testing was to compare the results of in situ dyeing to traditionally dyed, commercial casein fibres. Colour intensity, energy intensity and time-space yield (product yield per unit against time) were measured to assess the potential benefits of in situ dyeing. Commercial casein fibres were dyed at pH 2, at 40, 60 and 80 ˚C, following the basic method outlined in Ex 7 (p138). This experiment was still ongoing at the time of writing. The results were analysed by Keracol and contributed to Research Paper 6 (Appendix 10.6.6).

5.4.4 Ex 16: Weaving With Casein Filament

Aim: To compare aesthetics and material properties of textile samples woven with lab-produced, casein monofilament to those woven with commercial casein yarns and to determine their suitability for transient garments.

Location: Studio (HAG)
Collaborators: HAG, JH
Tools/Materials: 16-shaft table loom, warping mill, shuttles, raddle, reed, threading tools, Lab-produced monofilaments: x2 reels of undyed filament (1A/1B), x2 reels of BCP dyed monofilament (2A/2B),

Method: The filaments used in this section of research were spun using the completed ESR and drying system. Four reels of monofilament were sent to HAG, consisting of two undyed reels (1A, 1B) and two BCP dyed reels (2A, 2B). The dyed reels were coloured during the spinning process in a wash bath of 1wt% BCP and 5wt% sulphuric acid.

This experiment was conducted in two parts. In the first part, a collaborative assessment was

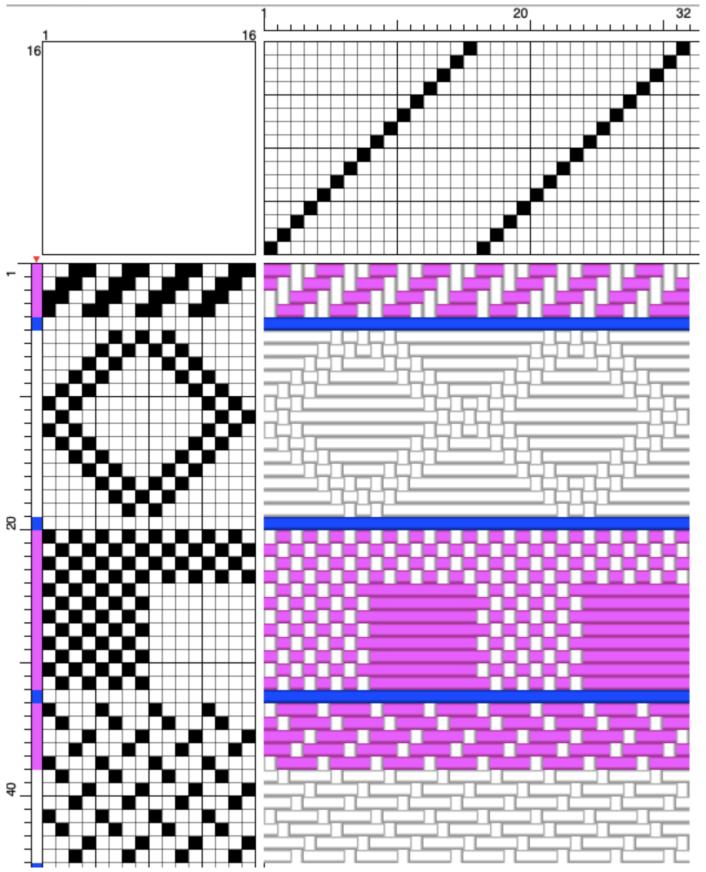
conducted with HAG in the studio to evaluate the filaments' characteristics and identify potential issues during setup, such as filament snapping or snagging. Handling the filaments made it apparent that their strength was inadequate for warp and weft. Consequently, a decision was made to opt for a 2/120NM silk yarn warp instead. Silk was chosen over cotton or any other kind of fibre as it is also a protein fibre and offered a similar weight/fineness to the filament. Although in industry, this would affect the composition and compostability of the material (assuming that the silk has been chemically treated during processing), using the silk at this stage still allowed us to create a unique range of casein-based textile samples and to understand what improvements are required at lab-stage to make the filament suitable for weaving.

HAG weaved an initial sample to assess the weaving quality of each yarn. A 15cm silk warp was set up, and four 3cm strips (one using each reel of filament) were woven in a plain weave. During weaving, HAG noted that the weft broke several times, informing the decision to use only reels 1A, 2A and 2B in the final sampling process. The speed and yarn tension was also adjusted to accommodate the yarn's delicate nature.

Figure 125 - 126: Weaving of lab-produced, monofilament test strips.

Regarding each reel of monofilament, HAG provided the following feedback:
Reel 1A: (Undyed) Flexible and wove well.
Reel 1B: (Undyed) More brittle than 1A and was challenging to work with due to snapping.
Reel 2A: (Dyed) Had a pale colour and wove well but was more liable to snapping than 1A.
Reel 2B: (Dyed) Had a darker colour and wove well.

Next, four further samples were developed using the previously set up silk warp to demonstrate different properties of the yarns and explore structure. Figure 126 shows the weaving draft and reels used for each sample.



Sample 1:
Weft Reel 2A – 2/2 Twill weave

Sample 2:
Weft Reel 1A – Honeycomb structure

Sample 3:
Weft Reel 2B – Plain weave with floats

Sample 4:
Weft Reels 1A + 2B – Satin weave

Figure 127: Weaving draft for final range of lab-produced, monofilament textile samples.

Results: HAG provided her initial observations when working with the monofilament:

"The yarn is brittle and has become coiled around the bobbins it has been stored on. It is liable to spring off the bobbin in coiled form. This combined with the slightly brittle quality makes it more difficult to work with. This yarn being a monofilament construction meant it was quite different to the spun fibre yarn used in previous sampling. It was stiffer and more delicate, leading to a very different sample. It was also significantly finer, meaning the final samples were more delicate and lightweight." HAG

Despite the brittleness of the monofilaments, the four final samples had a soft and flexible finish. Sample 1 (2A) was the softest of the samples and had the lightest weight. The surface was smooth and glossy with a consistent pale pink colour.

Sample 2 had a rougher, wiry texture due to the raised honeycomb weave. This weave also provided a highly decorative surface and would make an interesting finish for a shirt or dress with a more structured shape. Sample 3, woven with the darker dyed monofilament (2B), again had a weightier but subtle feel. The weave floats gave a soft pink, checked pattern and added a nice texture to the sample. Sample 4 was the heaviest of all of the samples. Again, it had a wirier feel and was rougher in texture but still flexible with a glossy finish. The weft of the material was left longer at the edges to demonstrate the curly nature of the monofilaments.

Figure 128: Woven monofilament Sample 1.

Figure 129: Woven monofilament Sample 2.

Figure 130: Woven monofilament Sample 3.

Figure 131: Woven monofilament Sample 4.

Overall, the samples demonstrated a much sturdier feel than expected, whilst using a silk warp gave the material a soft and pliable finish. The material has little drape but does have a beautiful sheen and transparency. Considering the R&D process required to produce the yarn samples, the weaving was successful and showed great potential for further material development. Compared to the flimsy nature of the commercial casein fabric and the fluffy, silky feel of the woven samples from Ex 12, the results of this experiment further demonstrate the range of possibilities regarding the material properties and aesthetics of casein-based materials.

As observed by HAG, the following steps would include improving the tensile strength of the filament and reducing the brittleness. Long-term development could involve turning the monofilament into short fibres, which could then be spun.

Reflection: The weaving work conducted in Experiments 10 – 12 (p155-167) laid essential groundwork for weaving with casein filaments. This previous experience allowed us (as a team of transdisciplinary researchers) to recognise notable differences in working with lab-scale filaments compared to commercial casein yarns. Commercial yarns generally possess consistent and well-defined properties, allowing for predictable weaving outcomes. In contrast, lab-scale filaments present unique challenges due to variations in strength, texture, and uniformity. These distinctions necessitate a comprehensive exploration of casein-based filaments' novel properties and behaviours.

Moving forward, the focus in response to the vision is on the compostability of the textile materials used and developed in this chapter. However, the filaments must still possess sufficient strength for textile construction and wear, even if designed for limited use before disposal. Among the main challenges encountered during this experiment was the low tensile strength of the monofilament, meaning that a fine silk yarn had to be used to make the warp. While the choice of silk facilitated the weaving process, it also revealed that the filaments require further development to attain the necessary strength for a 100% casein (mono)material. This realisation highlights the importance of investigating cross-linking agents and optimising the wash bath and acid usage to enhance filament strength.

5.4.5 Applying the Outcomes Of Knowledge Integration: Ex 13-16

Working with the ESR provided unique insights into textile fibre development that are often unavailable to textile designers. This practical understanding of the spinning process has facilitated greater collaboration between the designer (myself) and chemist (JH) in exploring specific material properties during the spinning stage. For instance, by adjusting the take-up speed to 1.5m/min, some of the challenges encountered during initial spinning demonstrations were overcome, resulting in finer, softer, and more flexible filaments.

Working side-by-side in the lab also allowed better communication and decision-making between the designer and chemist. Whereas previously, results were shared in hindsight through discussions and reports, working together in real-time allowed the designer to be a part of the decision-making process and form a deeper understanding of how such decisions affect final materials and outcomes.

Using the ESR and replicating established techniques contributed to a deeper understanding of historical challenges and the use of formaldehyde as a cross-linking agent. This first-hand experience provided a new perspective on the historical challenges found in the literature, such as low wet-tensile strength.

As well as a textile dye, BCP was considered as an alternative cross-linking agent. During the development of woven samples using dyed and undyed casein filaments, HAG found that the darkest dyed monofilament (2B) was the most pleasant to work with due to its flexibility and lack of snapping compared to the other reels. This positive result demonstrates the possibility that the BCP has played a part in defining the materials' properties and may have slightly improved tensile strength. Further analysis is needed to determine its impact on filament quality. (As a comparative study, testing in this area is conducted in the next section (5.5.1) using commercial casein yarns.)

Collaboration with HAG expanded the project's scope and provided unique insights into lab-spun casein filaments that otherwise would not have been possible. This collaboration bridged the gap between chemistry-based and textile-based investigations and informed the design of TCGs, as documented in Chapter 6. The following stage documents a series of material tests conducted on commercial and lab-produced casein materials, exploring their suitability within the vision.

5.5 Material Testing

Material testing was the final stage of this chapter before moving into a garment design perspective. The following experiments tested a range of hypotheses developed throughout this chapter and were conducted using various casein materials depending on availability and test requirements. As disposability has been highlighted as one of the main aspects of the RDF, durability and compostability were selected for testing. Specifically, the degradation rate of casein fibres and the tensile strength of dyed and undyed yarns were analysed.

JH and I carried out Ex 17 at UoL to compare the strength of dyed and undyed casein yarns. The results of this testing added to the discourse surrounding the hypothesis developed in Ex 3 (5.2.3), which questioned the use of specific natural dyes as a cross-linking agent capable of affecting textile properties and functionality. The results of this section and section 5.4.3 give way to a range of future research proposals in wet-spun dyeing and using tannins and anthocyanins as effective cross-linking agents for RPFs.

Experiments 18 and 19 were conducted by Eurofins BLC Leather Technology Centre Limited to investigate the compostability of casein as a textile fibre. Modified versions of the BS EN ISO 20200 test were employed to evaluate the disintegration level of casein in compost and its effect on soil quality and plant growth.

Four possible stages of the BS EN ISO 20200 were identified depending on the level of disintegration achieved at each stage. These stages include thermophilic testing, mesophilic testing, EcoTox soil analysis, and plant growth response testing. The impact of casein disintegration on ecological and toxicological effects can be assessed by evaluating the compost matrix, analysing chemical compounds, and observing plant growth.

Learning Process

During the testing process, close collaboration between JH and myself ensured a clear understanding of the experiment aims and effective use of available materials (e.g. how much filament could physically be made at the time). Tensile testing was conducted on a range of dyed and undyed casein yarns due to the limitations of the available equipment for testing monofilaments. Additionally, discussions with Eurofins BLC and JH helped determine suitable testing methods for compostability, providing valuable insights into the requirements and standards for evaluating compostable materials.

It is important to note that industry-standard testing methods are often limited to established materials such as plastics and leather. Hence, developing modified tests specific to casein fibres was necessary to accurately evaluate their properties and performance.

5.5.1 Ex 17: Tensile Testing (Commercial Fibres)

Aim: This testing aimed to compare differences in strength between each type of yarn and clarify whether natural dyes can improve textile properties and functionality.

Location: UoL
Collaborators: JH
Tools/Materials: Casein yarns, James Heal Universal Strength Analyser, weighing scales, Excel.

Method: Tensile testing was conducted on bulky weight dyed and undyed casein yarns. Avocado-dyed yarns were selected for testing due to the inclusion of natural tannins within avocado dyes. It was hypothesised that this would give the dye a better chance of improving tensile strength.

The yarns used were offcuts from Ex 12 (p165) and included yarns 2A (dyed) and 2B (undeyed).

Yarns Tested	No of Specimens	Jaw Scheme	Jaw Separation	Load Cell	Break Detection	Pretension	Speed/min
Bulky weight, undyed (2B)	5	T5	100.00mm	5000N	50%	0.10cN	20.00mm
Bulky weight, avocado dyed (2A)	5	T5	100.00mm	5000N	50%	0.10cN	20.00mm

Table 25: Comparison of tensile testing perameters.

10cm of each yarn was tested using a James Heal Universal Strength Analyser equipped with T27 or T5 Jaws with a jaw separation of 100mm. A modified version of the standard ASTM D2256 test was performed for lab purposes. The modifications included using shorter yarns (50cm of each yarn was used to perform x5 repetitions) and fewer repetitions (5 instead of 10) due to the use of offcuts and a limited supply of yarn. A pretension of 0.1 centinewtons (cN), 20mm per minute speed, and a break detection of 50% were used.

Each test was repeated five times per yarn, and the average (av) was used for the result. Data is reported in both cN/TEX: force required to break the yarn in cN per linear density of the tarn measured in TEX (the mass in grams of one kilometer of fibre). The TEX was measured for each yarn by taking 3x 50cm of yarn and averaging the weight to 5 decimal places.

Results: The results show a clear correlation between yarn weight and tensile strength, indicating that avocado dye (or other natural dyes containing tannins) could improve the tensile properties of casein yarns.

The enhancement in tensile properties observed in the dyed casein yarn can be attributed to the interaction between the avocado dye's tannins and the protein structure of the casein fibres. Tannins are naturally occurring polyphenolic compounds found in various plant materials, known for their ability to form strong complexes with proteins (Prabhu & Bhute, 2012). In the context of casein yarns, the tannins from avocado dye likely bind to the protein chains of the casein fibres, leading to improved cohesion and intermolecular interactions within the yarn structure.

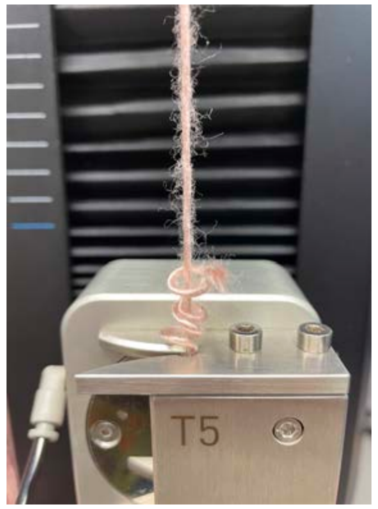


Figure 132: Tensile testing of commercial casien yarn - avocado dyed

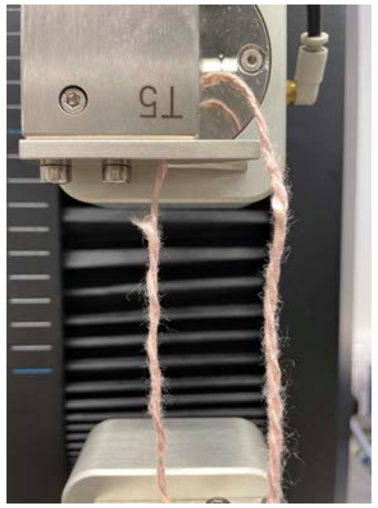


Figure 133: Avocado dyed fibre at breaking point.

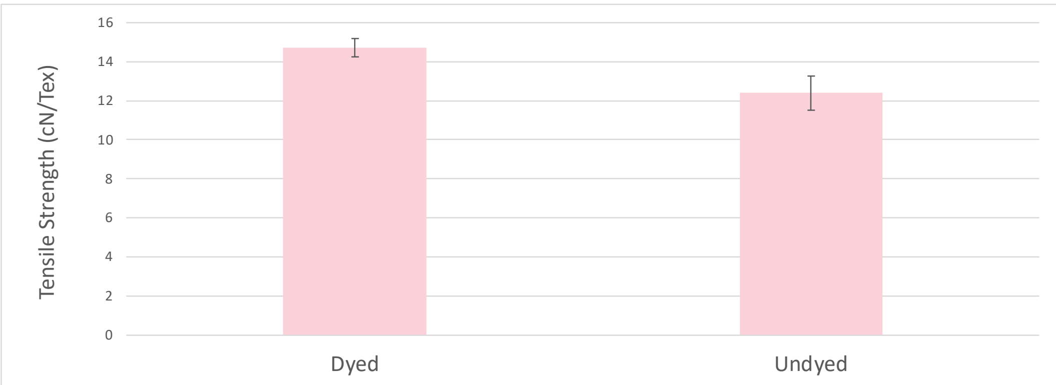


Chart 5: Demonstrates the recorded tensile strength between yarns (cN/TEX). The bar at the top of each column represents stdev (the spread of data).

Reflection: While the visual and tactile assessment of BCP dyed materials, particularly in weaving, suggested some impact on material strength, a stronger picture emerged with avocado dye. The increased tensile strength and elongation at the break of the avocado dyed casein yarns suggest that the dyeing process not only imparts colour but also contributes to the overall mechanical integrity of the yarns.

This preliminary exploration prompts a clear need for further testing. Replicating Ex 15 with an avocado-based dyestuff could shed light on this hypothesis, unravelling the impact of natural tannins during wet spinning and fibre formation.

Expanding the range of dyed casein materials for comparison would also be insightful. A deeper understanding of the dye's role in altering tensile properties could be obtained by comparing the weight and tensile strength of materials dyed with tannins against those dyed with anthocyanins (as found in BC dyes).

Future research could delve deeper into the mechanisms by which tannins interact with casein fibres, exploring how these interactions affect the microstructure and morphology of the yarns. Moreover, studying these dyed yarns' long-term durability and stability under different environmental conditions will provide a comprehensive understanding of their potential applications.

The utilisation of avocado dye and other natural dyes containing tannins has exhibited the potential to enhance the tensile properties of casein yarns. This finding opens avenues for sustainable textile production and encourages further exploration of natural dyeing techniques. By integrating traditional knowledge of natural dyes with modern scientific methods, researchers and industries can collaborate to create innovative, environmentally friendly materials that meet the demands of a regenerative economy.

5.5.2 Ex 18: Thermophilic And Plant Response Testing (Casein Fibres)

Aim: To investigate caseins' suitability as a compostable textile fibre and determine the degradation rate and impact on soil quality of commercial casein fibres.

Location: Lab (Eurofins BLC Leather Technology Centre Limited)
Collaborators: JH, Eurofins BLC Leather Technology Centre Limited
Tools/Materials: Casein fires, synthetic compost (Appendix 10.4.1).

Method: 1kg of commercial casein fibre was sent to Eurofins BLC Leather Technology Centre Limited for testing (enough to allow for all four possible stages of testing).

Depending on the level of disintegration achieved at stage one, the four possible tests are:

Stage one: Thermophilic testing – Samples are incubated inside a compost matrix at 58 (+ 2) ˚C for 90 days. If insufficient disintegration is recorded during the thermophilic assessment stage, the test continues to stage 2.

Stage two: Mesophilic testing - Samples are reintroduced into the compost matrix and incubated at 25 (ǂ 2) ˚C for 90 days. Post incubation, the level of disintegration is again evaluated gravimetrically to provide an overall percentage of disintegration.

Optional Extras - Post Disintegration Compost Tests

Stage three: EcoTox Soil Analysis - Assessment of the final compost matrix can be evaluated for various chemical compounds. This indicates the ecological/toxicological effects on the compost matrix resulting from any material disintegration that may have occurred during the ISO 20200 assessment.

Stage four: Plant Growth Response Testing - Assessment evaluating plant response to composted material can also be performed to indicate the effects on soil quality and plant growth after the ISO 20200 disintegration process.

Out of the four possible tests initially selected (Thermophilic, Mesophilic, EcoTox Soil Analysis, Plant Growth Response Testing), Thermophilic testing was conducted on both the commercial casein fibre and the lab-produced filament, and Plant Growth Response Testing was conducted on the commercial casein fibre.

Results: Thermophilic Testing (Casein fibre): During the thermophilic incubation period, the test sample was incubated with synthetic compost at 58±2°C for 90 days. After this 90-day period, the sample had disintegrated by 15.76%.

The plastic industry specification (BS EN 14995:20061) that informs the requirements of EU Directive 94/62/EC states that in terms of disintegration, a material is said to be disintegrated in compost if no more than 10% of the starting material is retained by a 2 mm sieve, after the thermophilic incubation period.

84.24% of the test sample was retained by a 2 mm sieve after the thermophilic stage of the laboratory-scale ISO 20200 (modified) test. Therefore, if this substrate were applicable and tested against BS EN 14995:2006 requirements, this substrate (in its current state) would not be considered a candidate for the disintegration element of the compostability requirements.

Results: Plant Response Testing (Casein fibre): For this test, Composts with and without the remaining fibre were analysed in accordance with REAL CCS v3.1, plant response and weeds test for composted material, to evaluate the influence of degraded material on the resultant compost. These results were measured regarding top growth, plant height, and true leaf number. After 28 days, the results suggest that the casein fibres grew more than the blank samples but less than the control sample. The mean top growth fresh mass (TgFM) of the test trays (per plant) as a percentage of the mean TgFM of the Blank trays (per plant) was 131.19%. The mean TgFM of the Test trays (per plant) as a percentage of the mean TgFM of the Control trays (per plant) was 74.74%. The test plants also showed no evidence of deformations.

In conclusion, these results demonstrate that adding casein fibres to compost can increase plant growth compared to the blank samples, but not as much as the control samples. The plants showed no unusual shapes or abnormalities, indicating that the compost with casein

fibres is safe for plant growth.

	Weight g			Mean TgFM
The total top growth fresh mass of Blank at 28 days:	32.8	34.5	35.3	**3.54**
The total top growth fresh mass of Control at 28 days:	55.3	69.6	61.4	**6.21**
The total top growth fresh mass of Test at 28 days:	52.4	32.6	49.6	**4.64**

Table 26: Comparative TgFM of Blank, Control, and Test Sample plants at Day 28.

Sample 1 **Sample 2** **Sample 3**

Figure 134: Comparative growth of 1) Blank, 2) Control or 3) Test Sample plants on day 28 showing the tallest and shortest plant out of the triplicates. Blank image has been adjusted to correct for scale.

Reflection: The outcome of this study presents a positive perspective on the regenerative properties of casein-base materials. While the thermophilic testing revealed a relatively low level of disintegration among the casein fibres, subsequent plant response testing unveiled the potential to contribute to improved soil quality through composting. This demonstrates the likelihood of casein proteins positively affecting soil quality, which could extend to other casein-based materials.

It is important to acknowledge that despite these mixed findings, a definitive explanation for the hindered degradation of these fibres couldn't be determined at this stage and could be influenced by multiple factors. One prominent consideration is that these fibres' manufacturing process may still involve using formaldehyde. This chemical serves a dual purpose – functioning as a cross-linking agent to support the fibres' structural integrity and lifespan while exhibiting antimicrobial properties. This antimicrobial attribute is particularly notable, as it could inhibit the activity of microorganisms that play a crucial role in breaking down the material during degradation.

A comprehensive analysis of the manufacturing processes, identifying the presence of formaldehyde or other additives, could shed light on the observed trends. Additionally, assessing the microbial activity in both the degradation process and composting environments might help clarify the extent of formaldehyde's impact on the decomposition of the fibres. One way to test this theory would be to test casein fibres that knowingly do not contain formaldehyde. This has been explored in Ex 19.

5.5.3 Ex 19: Thermophilic Testing (Casein Filaments)

Aim: To determine the degradation rate of lab-produced casein filaments (without the inclusion of formaldehyde) and compare them to that of commercial casein fibres.

Location: Lab (Eurofins BLC Leather Technology Centre Limited).
Collaborators: JH, Eurofins BLC Leather Technology Centre Limited.
Tools/Materials: Casein monofilament, synthetic compost (Appendix 10.4.2).

Method: 157g of lab-produced filament was sent to Eurofins BLC Leather Technology Centre Limited for testing (enough for stage one of Thermophilic testing only). Samples were incubated inside a compost matrix at 58 (+ 2) °C.

Results: During the thermophilic incubation period, the test sample was incubated with synthetic compost at 58±2°C. After 45 days, the sample had disintegrated by 100%, and the test was terminated. No mesophilic phase was required.

0% of the test sample was retained by a 2 mm sieve after the thermophilic stage of the (modified) laboratory-scale ISO 20200 test. In the results report provided by Eurofins, it was noted that if this substrate were applicable and tested against BS EN 14995:2006 (plastics – evaluation of compostability) requirements, this substrate could be a promising candidate for the disintegration element of the compostability requirements.

Reflection: The results of this test highlight a significant discrepancy in degradability between the lab-produced casein filament and the commercial casein fibres. This disparity is likely attributed to the absence of a cross-linking agent in the lab-produced filament, leading to a markedly reduced longevity when exposed to a composting environment. This experiment proves that the use of casein as a compostable fibre is definitely possible, however would still require careful consideration at production phase to ensure compostability is not compromised in other areas of manufacture.

Considering the outcomes from experiments 18 and 19, one could hypothesise that the lab-produced filament would have yielded a positive plant response, given its shared composition with the raw material. Expanding upon these findings would necessitate EcoTox and Plant Response

Testing, enabling a comparison to experiment 18 and deepening our understanding of casein's potential as a soil enrichment agent. Moreover, repeating the tests with commercially available casein yarns and twill fabric would contribute to a more comprehensive grasp of contemporary casein materials and their practical applications.

Much like exploring tensile strength, a broader investigation into dyed casein materials would also be advantageous. By examining the disintegration rate and plant response across a spectrum of dyes, including both tannins and anthocyanins, a more nuanced understanding of the influence of dye type on degradation and plant interactions could be gained.

5.5.4 Difficulties And Limitations Of Lab-Scale Testing

The testing of casein-based materials encountered several limitations concerning time and material requirements. Testing was typically conducted towards the end of the project to ensure that the ESR was fully operational. While this approach allowed us to submit the highest quality filament for testing, it imposed a physical constraint on the quantity of filament that could be produced and sent for evaluation within the project's timeframe. This limitation was not exclusive to the ESR but is an inherent constraint of lab-scale production. Production would have needed to transition from lab-scale to pilot-scale to produce significant quantities of filament.

Considering the favourable results obtained from the thermophilic testing of casein filaments, it would have been ideal to perform all four stages of testing for a comprehensive analysis. However, accomplishing this would have required producing an additional volume of 1kg of filament, which is generally unfeasible at lab-scale and would have necessitated the involvement of an external company to manufacture the fibre.

It would have also been advantageous to examine spun-dyed casein filaments, especially for comparing the results of the Plant Response test with those of undyed casein filaments.

Other limitations arose due to the nature of the materials under investigation. As discussed (p44), no ISO testing mechanism is currently available for assessing the compostability of novel materials like casein, unlike established materials such as leather and plastics. Furthermore, the morphology of casein fibres posed challenges since existing testing methods are primarily designed for sheet materials.

Consequently, the BS EN ISO 20200:2015 standard test, devised for evaluating the disintegration level of plastic materials, had to be modified. Given the structural properties of casein fibres, an additional adjustment involved placing the fibres into mesh bags to measure material breakdown. However, this modification may have introduced unforeseen impacts on the test's validity.

5.5.6 Applying The Outcomes Of Knowledge Integration: Ex 17-19

The results from these experiments contribute to the discourse surrounding the use of specific natural dyes as cross-linking agents and their impact on textile properties and functionality. In conjunction with Section 5.4, these findings open avenues for future research in wet-spun dyeing and using tannins and anthocyanins as effective cross-linking agents for regenerated protein fibres.

These studies have underscored the substantial difference in degradability between lab-produced casein filaments and commercial casein fibres, driven by the presence or absence of formaldehyde which is a known anti-microbial. The promise indicated by experiments 18 and 19 encourages further analysis through EcoTox and Plant Response Testing. Extending these investigations to encompass commercially available materials provides a holistic view of casein's practical utility. The parallel exploration of dyed casein materials adds another layer of insight, elucidating the role of dyes in degradation and plant response. These avenues of inquiry collectively pave the way for a more comprehensive understanding of casein materials and their potential as environmentally beneficial agents.

5.6 Summary

This chapter has explored using casein-based materials within a regenerative design framework for textile production. The knowledge acquired throughout the chapter is centred around colour, material properties, and making informed design decisions. Collaborating with experts and exploring various techniques has broadened the understanding of casein-based materials and their potential applications in regenerative textile design.

Although some experiments produced unexpected results, the overall goal of creating a range of casein-based materials was accomplished, and a first-hand understanding of the chemistry behind various lab-based processes was achieved. This new understanding of casein and its material properties has contributed to creative ideas in envisioning new areas for design intervention. The main challenges at this research stage resulted from working at home or needing access to sufficient space or facilities. Even though such challenges were not ideal, working in this way encouraged a balance of independent experimentation and facilitation between researchers due to the need for additional guidance in creating materials such as casein films.

Further development of the lab-produced filament is required to improve durability and tensile strength. However, the results achieved here show a promising start and hold many exciting future opportunities. Although these filaments have been produced with no cross-linking agent, we could still create several textile swatches that demonstrated positive aesthetic and performance properties. The next stage of filament development would be to take what has been learned and developed here and begin a new phase of pilot-scale testing focusing on the inclusion of alternative, non-toxic cross-linking agents to improve properties such as tensile strength and usability alongside a more in-depth exploration of wet-spun dyeing. Scaling this research up would allow more significant quantities of filament to continue physical material testing areas such as thermophilic, mesophilic, plant response and EcoTox testing.

Experimentation with casein-based textiles, films and galalith has supported the possibility of mono-materiality as a route to creating regenerative garments. Creating materials in all three forms provided a unique chance to evaluate a new casein-based product archetype whereby all garment components - from fibre to fastenings - are entirely biodegradable or compostable. Eliminating toxic and harmful chemicals in the dyeing and processing of these materials would also prove valuable for compostability. Keeping inputs non-toxic and as safe as possible, such as using food waste for dyes, should mean that nothing harmful can be released into the earth or the environment upon disposal. Depending on the specific material inputs, there is an opportunity to provide nutrients for the soil, and the disposed item may act as a fertiliser. The concept of mono-materiality within fashion is further explored in the next chapter.

Figure 135 shows the simplified workflow for each material form explored through this chapter in relation to the ten methods within the transdisciplinary research framework. The vision constantly feeds into the design process of material and colour, influencing the opportunities for knowledge integration and action.

The key outputs include two collections of woven textile samples, one from commercial casein yarns and one from lab-produced monofilaments. These outputs are central to the garment development explored in the next chapter. Learnings from this chapter are applied to a new fashion concept which has informed a range of final textile artefacts demonstrating the aesthetic and performance properties of casein materials within the context of transient fashion for a regenerative economy.

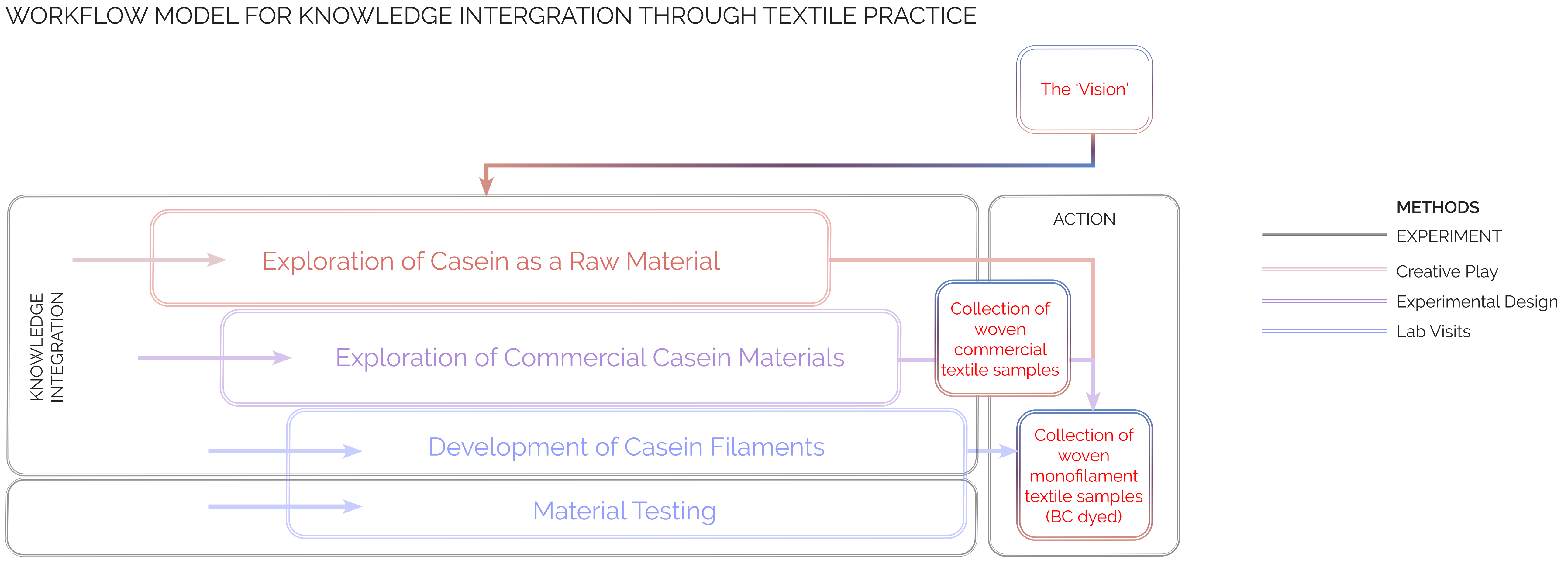


Figure 135: Workflow model for knowledge integration through textile practice.

6

PRACTICE 2: REGENERATIVE DESIGN THINKING FOR TRANSIENT CASEIN-BASED GARMENT

The following design activities build upon the foundations laid by the previous experiments (1-19), striving to apply the knowledge gained to unique contexts whilst developing proof of concept of the 'Vision' as set in Chapter 4. A range of material concepts are explored, from mono-materiality to no-sew garment construction methods and pattern cutting informed by historical techniques. Paper dresses are used as a case study to inform the practice and address obstacles by reappropriating historical techniques using green chemistry and regenerative design methods.

This chapter addresses research objectives 4 and 6 by documenting the creation of a range of transient casein-based garments (TCGs) for a regenerative economy, facilitating the quick and easy recapture of value through degradation. Using a systems-thinking approach to fashion and textile design, a range of mono-material design techniques were employed to demonstrate the aesthetic and performance properties of TCGs through a collection of supporting textile materials and toiles. These new endeavours seek to find novel expressions by seamlessly integrating the design and production of both form and textiles into a cohesive and simultaneous step. The objective is to develop efficient processes tailored for designing and manufacturing mono-material garments within a local, regenerative system.

6.1 Materials And Techniques

The knowledge acquired through Chapters Two, Four and Five converge in developing a distinct regenerative design practice. Emphasising collaboration and knowledge exchange, this chapter embodies an integrated, transdisciplinary framework that merges elements of fashion and textile design, chemistry, and historical practices.

Subsequently, a final design brief is formulated to showcase innovative design techniques in conjunction with casein-based materials, highlighting the aesthetic functions and properties of the resulting garments. The chapter explores an approach aligning the speedcycles of textile material and garment, achieved through the implementation of quick-to-make, low input, no-sew garment construction techniques. A comprehensive list of the techniques investigated in this chapter, along with the requisite skill set and their relevance to the creation of TCGs, is presented in Table 27.

Technique	Skill Set Used	Materials Used	Collab-orators	How does this aid the matching of speedcycles within a reg framework?
Textile gluing	Textile Design/ Chemistry	Casein fabric/ casein powder	n/a	Speeding up of manufacturing system/ ease of breakdown at end of life
Hand linking/ tying	Fashion Design	Casein fabric	n/a	Speeding up of manufacturing system/ ease of breakdown at end of life
Laser cutting	Fashion Design	Casein fabric	n/a	Speeding up of manufacturing system
Historical methods of pattern cutting	Fashion Design/ Historical Practice	Casein fabric	n/a	Speeding up of manufacturing system
Zero waste pattern cutting	Fashion Design	Casein fabric	n/a	Speeding up of manufacturing system/less material wastage
Garment design	Fashion design/ Textile design/ CAD	Casein fabric	n/a	Speeding up of manufacturing system/ease of breakdown at end of life

Table 27: Matching material technique with skill set within a regenerative design framework.

This chapter utilises commercially purchased casein materials and the researcher-made materials developed in Chapter 5 to explore and compare properties in terms of usability for garments. Although these materials were first developed in a range of locations between lab and studio (HAG), the garments and techniques discussed in this chapter were developed between making spaces at LCF and home, both digitally and physically, whilst utilising more traditional textile design and fashion design techniques.

Table 28 provides a detailed breakdown of each technique explored in this chapter, clarifying the specific materials and tools used.

Technique/ sample	Commercial Materials Used	Developed Materials Used	Tools used	Location/ Work-space	Refer to Section:
Ex 20: Casein Glue Sample 1 & 2	Purified casein (powder) 100% casein fibre twill		Magnetic stirrer, Beaker, scales Pipette,	Domestic (Kitchen)	6.3.3 (p222)
Ex 20: Casein Glue Sample 3	Purified casein (powder)	Commercial woven samples (plain weave & satin weave)	Magnetic stirrer, Beaker, scales pipette,	Domestic (Kitchen)	6.3.3 (p224)
Ex 21: Hand Linking	100% Casein fibre twill		Adobe Illustrator, Laser cutter	Domestic, LCF	6.3.4 (p226)
Ex 22: Hand Tying	100% Casein fibre twill		Adobe Illustrator, Laser cutter	Domestic, LCF	6.3.5 (p230)
Ex 23-25: Tie Together Top, Skirt & Dress (Pattern cutting)	100% Casein fibre twill, Calico		Paper sampling, Adobe Illustrator, Laser cutter	Domestic	6.3.6 – 6.3.8 (p232 - 237)
Ex 26: Tie Together Coat	Casein Yarns, Calico	Commercial woven samples	Paper sampling, Adobe Illustrator, Adobe Photoshop	Domestic	6.3.9 (p238)
Transient, Casein-Based Dress	Purified casein (powder)	Monofilament woven samples	Adobe Illustrator, Adobe Photoshop	Domestic	6.4.1 (p240)
Transient, Casein-Based Coat	Casein Yarns,	Commercial woven samples	Adobe Illustrator, Adobe Photoshop	Domestic	6.4.2 (p250)

Table 28: Material techniques mapped against materials and tools used.

6.2 Designing For Disposability

This section delves into the practical aspects of the RDF and the garment design brief, bridging the gap between theoretical concepts and real-world implementation. Until now, the RDF and TCGs have been primarily discussed in a hypothetical context. However, this section takes the first steps toward illustrating how these concepts can be effectively implemented within the industry and how they align with the overarching future vision articulated in Chapter 3.

The forthcoming two sections draw upon a synthesis of knowledge obtained from the Literature Review (Chapter 2), the Methodology (Chapter 3), the Consumer-based survey (Chapter 4), and the Practice (Chapter 5) visualising the development of local regenerative systems that harness the potential of food waste and their practical integration into both industrial processes and daily life. This exploration remains mindful of how TCGs fit into the broader global perspective, considering ecological sustainability and the social foundation.

6.2.1 Creating Local, Regenerative Systems From Food Waste

Adopting a mono-material approach in garment production influences the entire lifecycle by centring on a single raw material. This framework emphasises the importance of working with the raw material's natural properties and allowing these to influence the textile's structure, texture, and features of the resulting garments rather than vice versa. By respecting the raw material, the focus is on creating environmentally friendly fabrics, avoiding using harmful chemicals to alter their nature in line with the conventional notions of what a textile material *should* be.

In line with living system principles, this research advocates for a shift in perspective from viewing garments as mere objects to recognising the intricate relationships between the material, garment, and the earth. Within this paradigm, both designers and consumers play pivotal roles as facilitators in the garment's lifecycle. Embracing this approach entails collective responsibility to ensure ethical clothing production, care, and disposal. For example, if garments are designed to be 100% compostable, consumers must be educated on the appropriate care and safe disposal methods.

Figure 136 exemplifies a framework for a local and regenerative casein-based system, which harnesses casein extracted from local dairy industry waste. The prepared casein is transformed into diverse materials, including galalith, textiles, and films. To ensure a holistic approach, initial dairy and agricultural farming practices should align with regenerative methods in their supply chain. These practices encompass maintaining a high quality of life and good treatment of livestock, utilising organic and locally sourced animal feed, implementing renewable energy sources, and recycling waste, water, and animal manure.

Within this framework, final materials and garments are purposefully designed to cater to designated lifespans. Depending on the required structure and durability, garments can be re-sold or returned for upcycling, prolonging their lifespan in the supply chain. Garments designed for short lifespans can be domestically composted or repurposed as industrial fertilisers.

Adopting a mono-material and regenerative system necessitates transformative changes in how the industry and consumers perceive fashion and textiles. The conventional understanding of quality must shift from the user stage to the end of life stage, wherein the focus lies on the value that can be reintegrated into the system and eventually returned to the earth.

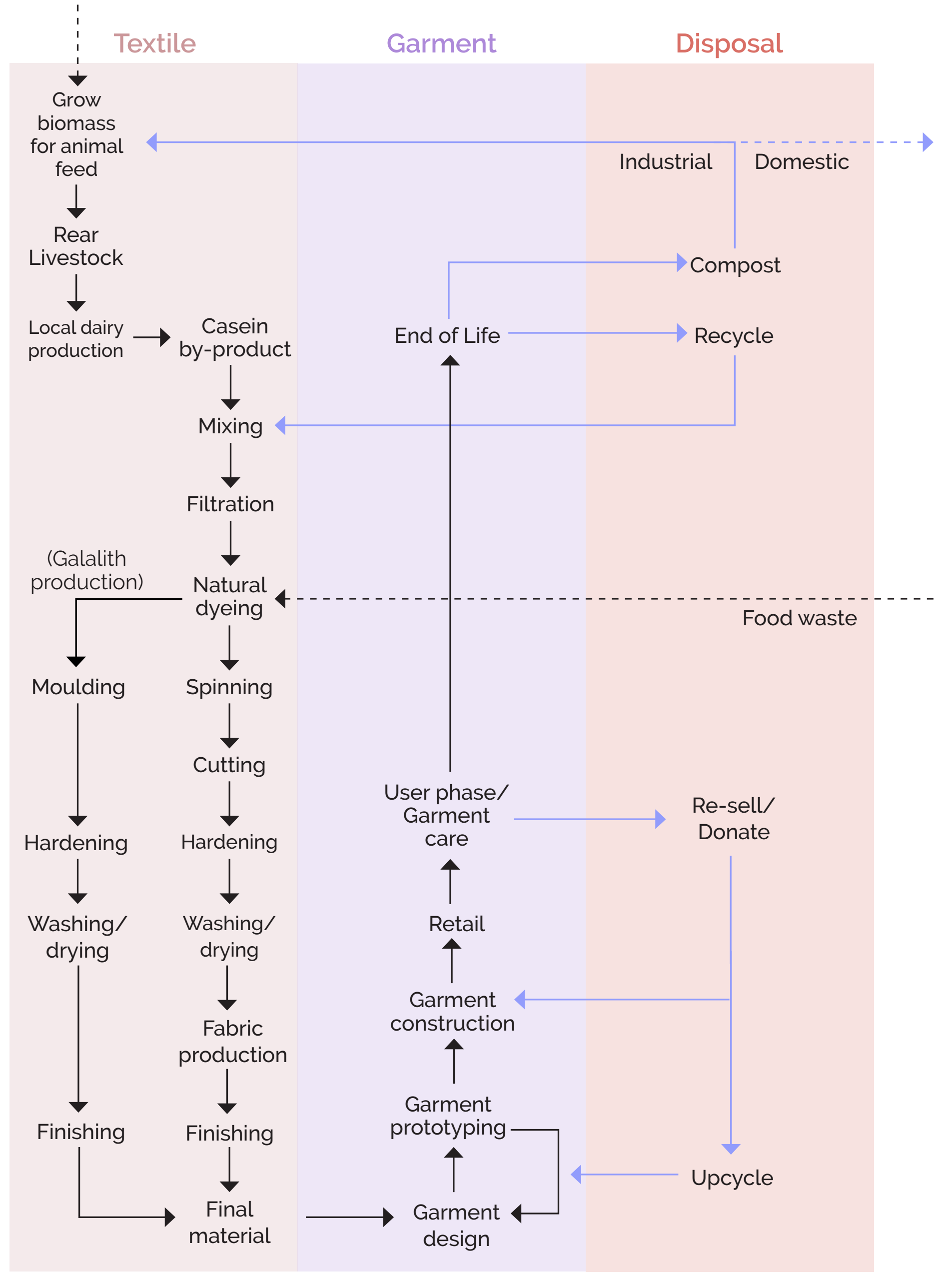


Figure 136: Example of a local casein-based regenerative system.

6.2.2 Garment Design Brief

The following design brief for creating TCGs addresses the key points derived from theory and practice based research conducted throughout this thesis by responding to the subsequent questions:

What is the overarching issue to be solved?
The central issue is the pervasive waste within the supply chain. This challenge encompasses waste at both pre-consumer and post-consumer levels, spanning various forms such as material, water, and chemical waste.

How will this issue be tackled?
The challenge of supply chain waste is addressed through the design of TCGs. A pivotal element in waste reduction is the regenerative aspect of these garments, allowing them to degrade within a specified timeframe. Achieving this goal involves adhering to regenerative design principles (3.2.2), necessitating a clean and non-toxic manufacturing process. This includes carefully considering the processing, colouration, and finishing of textile materials and garments. Additionally, the style of garments and cutting techniques are also considered, incorporating methods such as zero-waste pattern cutting.

What are the garment requirements?
A designated lifespan of one season (maximum six months) has been established for garments designed under this brief. This timeframe strikes a balance, allowing for a handful of wears within a short period without requiring excessive durability or compromising degradation time. The decision aligns with industry statistics indicating that garments are typically discarded after approximately ten wears (Pulse of the Fashion Industry, 2017).

As no official regulation specifies the speed of garment degradation for compostability classification (2.4.2, p43), a theoretical timeframe has been assigned within the brief. Smaller, lighter items such as tops or dresses are given a hypothetical degradation timeframe of 90 days, while larger pieces like jackets or coats are allotted 180 days to degrade. This selection is informed by the thermophilic testing conducted on casein filaments (5.5.3). Specifically, 157g of lab-produced filament disintegrated within 45 days when incubated with synthetic compost at 58±2°C. The ratio of the weight of the material to the time taken to decompose (157:45) guides the choice of 90 days for heavier garments (considering both material usage and weave density) weighing up to 350g.

While these requirements cannot be formally tested within the current project scope, they remain crucial factors within the RDF. Strategies to advance this design work and test it against the RDF are discussed in Chapter 7.

How will these requirements be met?
The design considerations for meeting the established requirements include assessing the quantity and weight of the material used and the chosen colouration and finishing methods.

While formal compostability testing of final garments is not conducted, valuable insights can be drawn from the material tests documented in Section 5.5 in conjunction with garment design techniques, aiding in assessing strengths and weaknesses in the final designs.

Within the scope of this brief, four types of garments have been explored to enable a comparison of techniques across various shapes and styles. Specifically, a dress, top, skirt and coat were selected to reflect diverse consumer expectations regarding performance and longevity, as indicated by insights from the consumer survey (4.1.2). Moreover, these garments align with the weights and properties of the commercial casein materials available at the time. For instance, the commercial casein twill is very lightweight and lends itself better to tops or dresses. In contrast, the bulkier casein yarns suit the creation of a coat or light jacket, considering the capabilities of the yarns.

As figure 137 demonstrates, this design brief is positioned within the broader vision and worldview, responding to the need for a local and regenerative economy. Beyond eliminating waste in its own supply chain, the brief capitalises on waste from other local industries, creating new value at multiple points in the various other supply chains. Depending on the scale-up of such garments, participating industries could encompass dairy (casein), restaurants/cafes (food waste dyes), supermarkets (food waste dyes), or other food preparation businesses.

The brief reflects the 'wardrobe' element of the broader vision and worldview, aiding the transition from a garment design perspective to a regenerative system thinking perspective (3.2.2).

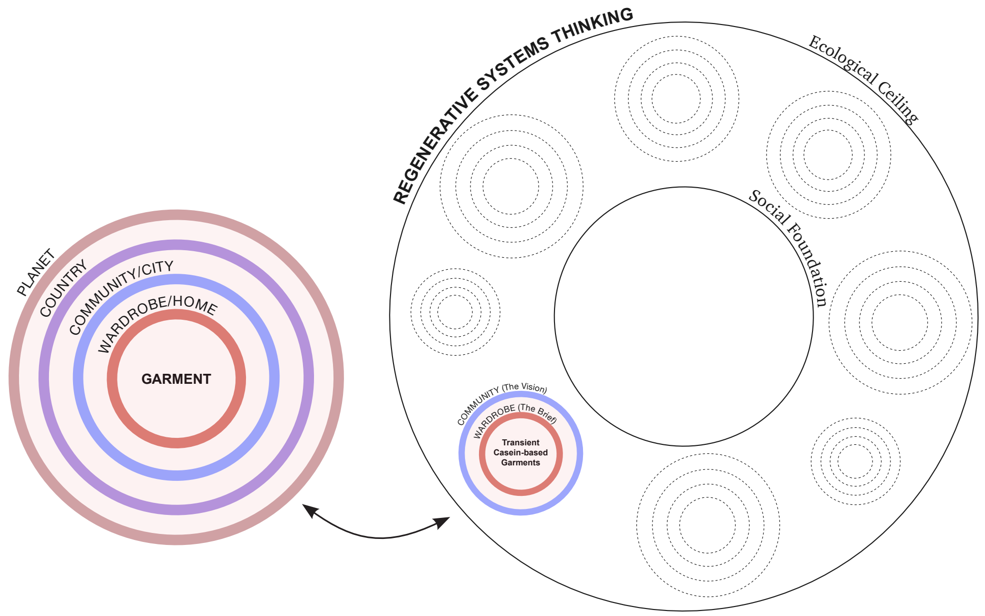


Figure 137: Demonstration of how the brief sits into the broader vision and worldview (between the ecological ceiling and social foundation, alongside other communities and industries). Adapted from McQuillan's (2020) zero waste systems thinking model.

6.3 Mono-Material Garment Design

The research has shown that casein provides an exciting opportunity to design a unique, mono-material garment archetype. This archetype has been explored in the following section by breaking down traditional garment construction methods and rethinking the conventional garment design process. Not only were components such as fastenings or decorative features limited to what could be made in casein, but the sewing of seams and hems also had to be considered to avoid introducing a cotton or polyester thread to the garment.

The garment design process in this study draws inspiration from historical research, including paper dresses from the 1960s, the kimono, and Balenciaga's 'one-seam coat' (V&A, n.d.b). It also incorporates contemporary design practices such as zero waste (McQuillan, 2020), design for disassembly (Forst, 2020), and simultaneous design (Townsend, 2003). This approach merges textile and garment-led design, considering both aspects from the outset of the design and development process. By designing the fabric and garment simultaneously, the designer can modify the print scale and placement alongside garment shaping (Townsend, 2003). Although this technique is commonly associated with digital printing technologies and 3D design software (Townsend, 2003), it can be applied to craft-based processes like screen-printing.

The design process involved fabric samples, toiles, and paper models to experiment with garment shape and construction techniques. Adobe Illustrator was used to digitise the selected construction method and silhouettes, with garment features drawn as separate layers before importing into Photoshop to experiment with colour and print effects. Photoshop's layered image-building technique proved valuable in creating digital composite effects.

While more advanced technologies are available, the Adobe design suite is more accessible and requires no additional training. For future research, exploring 3D design software and pattern-cutting software like 3D Studio Max (Garment Maker) and Gerber Technology is recommended for more sophisticated outcomes.

This section reflects on the earlier work on paper dresses (6.3.1) through visits to the Metropolitan Museum of Art and the Brooklyn Museum to see two collections of paper dresses in person. This visit allowed for a more comprehensive assessment of the design and manufacturing techniques used at the time to inform a new range of no-sew garment construction and pattern-cutting methods.

The learning process for this experimentation involves utilising personal experiences and tacit knowledge. Visual learning techniques, such as mood boards and exploration of existing design techniques, played a significant role. Toiles and paper models served as reflective learning tools during the design process of TCGs. As well as paper dresses, Balenciaga's 'one-seam coat' acted as a reference point, inspiring the creation of simple and minimalistic garment silhouettes with fewer seams and joining points.

6.3.1 Design Research: Paper Dresses

This research section centres on the primary challenge of finding suitable methods for constructing garments without sewing. A thorough investigation was conducted to address this obstacle, incorporating primary and secondary research from various historical and contemporary sources. Paper dresses were explored as a potential source of design inspiration. Although a literature review provided insights into the origins and motivations behind paper dresses, information on the methods and materials used in their construction was limited.

Fortunately, an opportunity arose to visit the Metropolitan Museum of Art and the Brooklyn Museum, where two collections of paper dresses were held in the Museum's archives, providing a valuable opportunity for first-hand observation and exploration. The visit to the Metropolitan Museum of Art allowed the close examination of a collection comprising seven unique garments:

- Waste Basket Boutique by Mars of Ashville, 1966, Donated by Barbera Moore, 1986 (American)
- Evening dress by Elisa Daggs, 1967, Donated by Barbara Moore, 1986 (American)
- Dress by Paperdelic, 1967, Donated by Richard Martin, 1994 (American)
- Dress by Scott Paper Ltd, 1966, Donated by Janet Barrell Davis, 1995 (American)
- Dress by Joseph Love, Inc, 1967-1968, Donated by Joseph Love, Inc, 1968 (American)
- Dress by Joseph Love, Inc, 1968, Donated by Joseph Love, Inc, 1968 (American)
- Lingerie by Goujon, Ltd, 1967-1969, Donated by Brooklyn Museum 2009, donated by Hannah T. Rose, 1969 (British)

Figure 138: Met Museum - Elisa Daggs Evening Dress.

Figure 139: Met Museum - Scott Paper Dress.

Figure 140: Met Museum - Joseph Love, Inc Dress.

The second collection, viewed at the Brooklyn Museum, consisted of two dresses designed by Andy Warhol for the Waste Basket Boutique, manufactured by Mars of Ashville. Both dresses were made in America in 1966 and were donated by the artist shortly after.

Figure 141: Brooklyn Museum - Andy Warhol Banana Dress.

Figure 142: Brooklyn Museum - Andy Warhol Fragile Dress.

The ability to study these dresses up close enabled a deeper understanding of their construction techniques and design intricacies, supplementing the existing literature. Although physical contact with the garments was not permitted, examining them up close allowed a close estimation of the materials' weight and texture. Detailed photographs were taken of various features, including hems, seams, armholes, fastenings, and decorative elements like prints and stickers. This first hand look at paper dresses enabled a more comprehensive understanding of the construction methods employed.

Despite variations in each dress, common themes emerged regarding materials and construction. Simple dresses typically consisted of a back and a front piece, resembling shift dresses. Sleeves, if included, were not separately attached but instead shaped directly into the pattern and sewn along the sides and across the shoulders in a batwing style. Surprisingly, the dresses displayed better finishing than anticipated for disposable items.

In some cases, bias binding made from a polycotton blend was used to finish armholes, necklines, and sleeves, while fastenings such as plastic zips or ties were employed on the back of the neck. Side seams were machine-stitched and reinforced with overlocking using polyester thread. In contrast, hems at the bottom of the garments were generally left raw, as the 'paper' materials did not fray. Interestingly, the materials were often bonded with a reinforcing layer to enhance durability and give a stiffer appearance, which suited the shift dress style.

Although it was visible that dresses had been put together quickly, the evidence of reinforcements and the introduction of plastic-based materials (in the threads and bias binding as well as decorative inks and stickers used) seemed unnecessary for a disposable item which cannot be washed and was designed to be thrown away after up to three wears (Auerbach George, Tregenza et al., 2023; Thomas, 1966).

One intriguing feature of the paper dresses was their customisability, achieved through stickers and paint packs, allowing wearers to decorate the garments directly. While customisability is often explored in a contemporary sustainability context as a way to extend the lifecycle within a slow fashion framework (Black, 2012; Forst, 2020; Goldsworthy, 2012), in this case, it served more as a gimmick. Nevertheless, the manufacturing perspective of reducing production volumes by designing a capsule collection of unprinted items with various means of customisation offers a contrasting insight.

Figure 143: Metropolitain Museum - Waste Basket Butique customising kit.

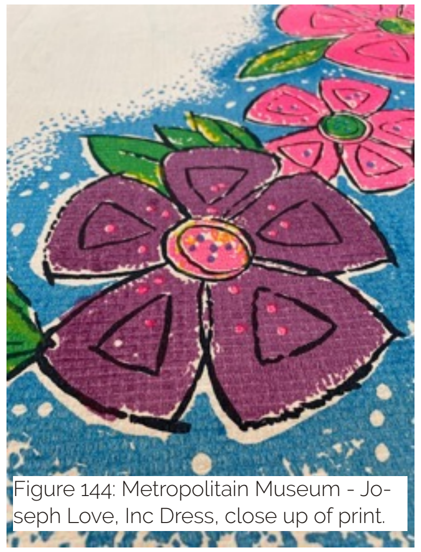


Figure 144: Metropolitain Museum - Joseph Love, Inc Dress, close up of print.

6.3.2 Design Research: No-Sew Methods Of Garment Construction

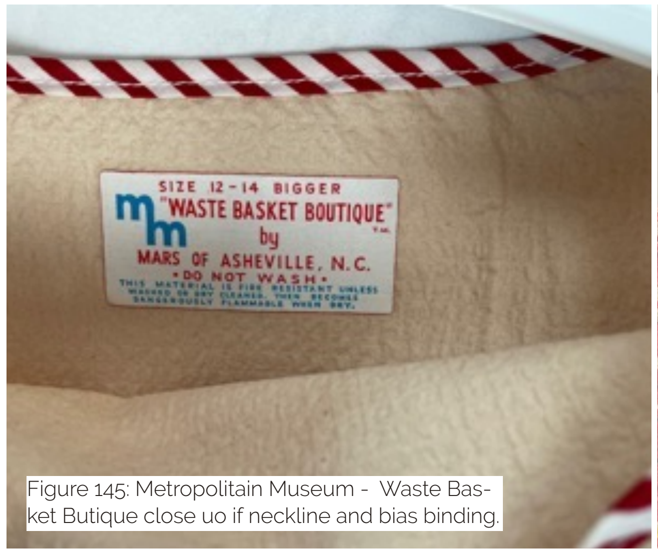


Figure 145: Metropolitain Museum - Waste Basket Butique close uo if neckline and bias binding.

Figure 146: Metropolitain Museum - Scott Paper dress close up of shoulder featuring bias binding.

The exploration of paper dresses sparked a contemporary quest for garments featuring alternative methods of adding decoration or creating three-dimensional shapes without traditional stitching. Mood boards 1-3 showcase a selection of historical and contemporary references from this search. These garment construction techniques depart from traditional stitching methods, presenting innovative and customisable approaches to sizing, silhouette, and decorative features.

Designer Katie Roberts-Wood adopts a distinctive approach to garment construction, utilising her signature hand-linked, non-stitch method in combination with digital embroidery and pattern making (Roberts-Wood, n.d.). This unique approach of attaching and joining fabric results in organic and distinctive structures within the garment. Although the exact process remains undisclosed, it appears that slits in the fabric are used to loop the ruffles through and back onto themselves.

Phoebe English's Autumn/Winter 2015 collection showcased delicate recycled net garments adorned with silk ropes woven, knotted, and tied between open spaces, creating intricate and flowing patterns across the body (Singer, 2015). This innovative method of joining and attaching fabric without sewing opens possibilities for customisable patterns and textures, which the wearer can explore over a basic garment.

In his Pre-Fall 2016 collection, Christopher Kane featured several garments that play with open spaces by attaching blocks of fabric with cord loops, acting as a lace insert to create transparency and contrast to the main body of the garment. Although these fabric layers or blocks are not removable, the concept lends itself to incorporating attachable lengths of fabric, allowing the wearer to modify the skirt or dress length without cutting.

Mood Board 1: No-sew methods of garment construction & detail

Images 1-4: Examples of Roberts-Wood Hand linked ruffle technique as a decorative feature.

Image 5-6: Christopher Kane, Pre Fall 2016. Christopher Esber, knitted dress - Attachable/detachable layers.

Image 7: Phoebe English, A/W 2015 - Use of open spaces and tie together fabrics.

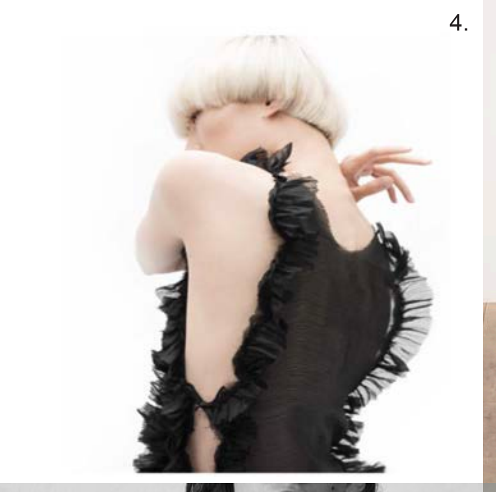


Figure 147: Mood Board 1: No-sew methods of garment construction & detail.

Mood board 2 presents diverse historical and contemporary examples, inspiring the design experimentation. From high-end couture to commercial and domestic sewing markets, each example offers a unique perspective on creating simple yet effective garments with minimal detail.

Historical examples, such as Pierre Cardin's couture 'Tabard' Dress with adjustable tie sides and Butterick's two-way wrap dress pattern, provided insights into simplistic garment design. Issey Miyake's 132 5 Stitched Hole Dress inspired a more contemporary approach, requiring minimal sewing to achieve its structured shape.

Commercial examples, like the Ragged Priest's 'Milk it' Knit, offered contrasting methods, embedding ties into the garment through knit or weave instead of cutting. Additionally, the unique pattern-cutting method of designer Katie Roberts Wood was drawn upon again, incorporating larger origami-style ruffles that flow across the garment. All examples offer a different technique or perspective in creating a simple yet effective garment with minimal detail.

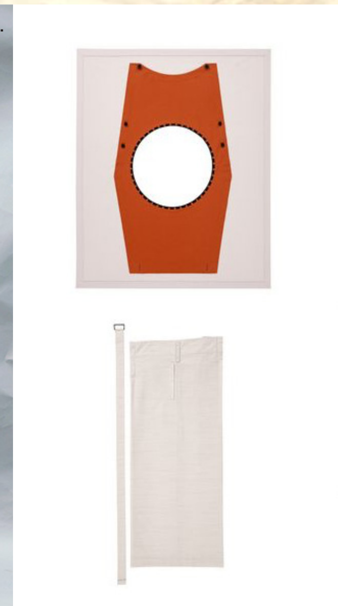
Mood Board 2: Garment shape & sizing.

1.

2.

3

4.



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Examples of garments constructed with minimal seams and simple pattern pieces in loose fitting, adjustable shapes.

Image 1: Pierre Cardin 1960s Couture Ethnic Print Tabard Dress

Image 2: Butterick Two Way Wrap Dress Pattern

Image 3: Balenciaga, 1966. Silk cocktail dress

Image 4: Roberts Wood, Dover Street Market

Image 5: 132 5. Issey Miyake dress, Stitched Hole

Image 6: Ragged Priest, Milk it Thread Knit

6.

Figure 148: Mood Board 2: Garment shape & sizing.

Mood board 3 demonstrates several versions of the one-seam coat, initially designed by Balenciaga in 1964. Over time, this iconic coat was constructed in varying materials and shapes but generally featured a batwing or cape-like sleeve and a cocooned silhouette. Famed for his reinvention of the female silhouette and moving away from the traditional corseted waistline of the time, the exclusion of side seams to create fluid, architectural shapes was a signature style of Balenciaga's (V&A n.d.b). His fabric selection was crucial to his designs, often opting for heavier woven cloths, which were stiffer and helped to shape his silhouettes (Charleston, 2004).

Image 1 of mood board 3 shows a double-breasted even cape constructed from white gazar (silk organza). The design features a covered button fastening and a deep flounce seam (V&A n.d.a). Image 3 on the mood board shows a boxy day coat with three-quarter-length sleeves constructed with fancy-weave wool. The coat is single-breasted and cut from three panels featuring three self-covered buttons, a square turndown collar and two diagonal standing pockets (The Met n.d.). Patrick Kelly's take on the one-seam coat from 1985 was also explored and used as inspiration.

Although some of the techniques presented across these three mood boards may be considered artisan and unsuitable for the fast fashion market as it exists today, the underlying concept of regenerative, transient fashion reaches beyond mere market integration or replacement. As previously argued, the high fashion industry is equally culpable for producing garments intended for single occasions, relying on petrochemical-derived materials and conventional manufacturing techniques.

Inspired by Mood boards 1, 2 and 3, the presented samples delve into methods of laser cutting, pattern cutting, and developing a casein fabric glue as methods of joining fabric and creating shape. This hands-on investigation examines the suitability of each technique for different fashion sectors, weighing factors such as time, effort, skill level required for implementation, material usage, and potential production costs.

6.3.3 Ex 20: Casein Glue As A Method Of Garment Construction

Aim: To create a casein-based glue capable of bonding fabric without sewing and assess its potential as an alternative garment construction and finishing method.

Method: The idea to trial a casein glue emerged from developing casein films, mainly when used as a coating or biopolymer with casein fabric (5.2.2). The basic formula for casein dope was used wet as the glue:

- 300ml water
- 16g casein powder
- 3.5g $NaHCO_3$
- 8g $C_3H_8O_3$

Mood Board 3: The one seam Coat

Balenciaga's 'one seam coat' designs, are created by folding the material into shape to make sculptured designs.

Image 1: Balenciaga, Evening cape, 1963. V&A Museum

Image 2: Balenciaga, Kimono sleeve wool coat, 1964. The Metropolitan Museum of Art

Image 3: Balenciaga, Silk evening wrap, 1965. Metropolitan Museum of Art

Image 4: Balenciaga's One seam coat on display at the Metropolitan Museum of Art, 1973

Image 5-6: Patrick Kelly, One seam coat and pattern, Philadelphia Museum of Art, 1985

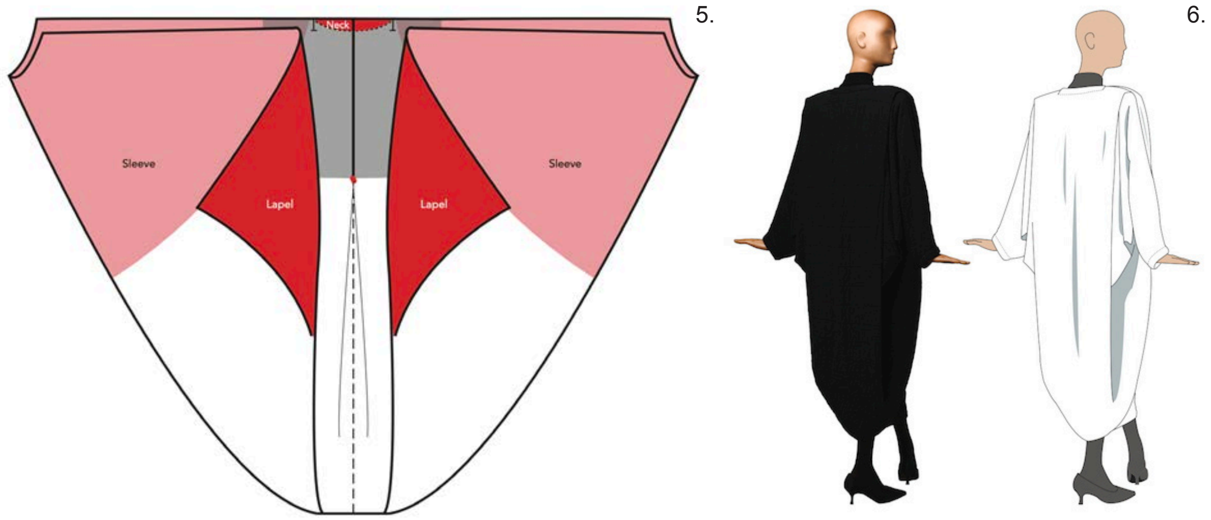


Figure 149: Mood Board 3: The One-Seam Coat.

Four samples were created for testing. The first sample was used to assess the glue on the casein twill fabric, while the second sample utilised previously dyed/screen-printed casein twill fabric to create a basic garment. Additionally, two more samples were tested using the earlier-developed woven casein samples.

Sample 1: The first trial involved using a micropipette to apply the basic casein dope directly to the casein twill in a French-style seam. The seam was then pressed in place and set using an iron.

Sample 2: In the second trial, casein glue was tested on an onion-dyed casein twill used to create a basic shift dress shape with shoulder and side seams. The glue was applied using a paintbrush for a neater application than previously achieved with the pipet. The wrong sides of the fabric were pressed together over the glued area, and another layer of glue was bushed on top. The two pieces of glued-together fabric were folded over 1cm and pressed into place.

Samples 3 & 4: Two samples of heavier, woven casein (plain and satin) were also used to test the casein glue. Rather than a joining seam, a simple hem was tested by applying a layer of glue to the top edge of the fabric and folding it over by 1cm before pressing with an iron.

Results:
Sample 1: The glued seam appeared reasonably neat and held together well when subjected to light pulling by hand—however, the glue soaked through the fabric, resulting in a slightly brownish stain along the seam.

Sample 2: Though the seams appeared sturdy, the glue seeped through the material again, leaving stains down the sides of the garment. Glueing the seams on the shoulders was easier than on the sides due to the shorter length, making it more manageable to hold in place and press in one go. (Refer to Figure 155).

Figure 150: Preparing the seam for glueing (Sample 2).

Figure 151: Glueing the shoulder seam (Sample 2).

Figure 152: Pressing the shoulder seam (Sample 2).

Figure 153: Pressing the side seam (Sample 2).

Figure 154: Final side seam (Sample 2).

Figure 155: Final shoulder seam (Sample 2).

Samples 3 & 4: In contrast to the lightweight twill fabric, the heavier, woven material was much easier to press in place, allowing for a cleaner, straighter line. The glue did not soak through to the material's surface, leaving no visible marks on the back or front. The heavier weight of the woven samples likely facilitated a stronger hold, providing a better surface area for the glue to adhere to.

Figure 156: Glued finish sample on satin weave (back) (sample 4).

Reflection: While casein glue may offer an alternative method for constructing and finishing garments when used with appropriate fabric, it is most suitable for straight lines. It would be challenging to apply neatly by hand on circular necklines or curved edges. Access to facilities like a heat press could aid the process, making it easier to press seams into place once glued.

The trials with casein glue highlight its potential for garment construction and finishing when used with specific fabric weights and straight seams or hems. While challenges exist, further exploration and testing with different fabric types and equipment will be crucial to fully understand the capabilities and limitations of casein glue in the context of sustainable and regenerative fashion practices.

Figure 157: Glued finish sample on satin weave (Front) (sample 4).

6.3.4. Ex 21: Hand Linking As A Method Of Garment Construction

Aim: This experiment aims to develop an innovative solution for creating garment shapes and structures, moving away from traditional sewing techniques like darting or ruching.

Method: Drawing inspiration from mood boards 1 and 2, the initial approach involved cutting slits into strips of casein fabric and looping them through each other to achieve a plaited effect. This method was initially executed through hand cutting; however, challenges with the lightweight nature of the commercial casein twill and its tendency to fray prompted a shift towards laser cutting as a more precise and controlled method of cutting.

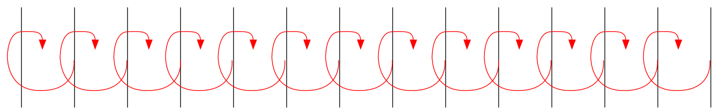


Figure 158-160: Initial, hand-cut samples exploring methods of linking to create shape within the fabric.

The study explored different sizes and placements of loops cut into the fabric to investigate linking as a construction method. A series of tests were conducted on the laser cutter, experimenting with various settings, including cut through, kiss cut, and engrave, to determine the optimal parameters for achieving a clean cut and reducing fraying. Adobe Illustrator was used to design the patterns, which were then converted to ESP files compatible with ApS-Ethos Laser cutting software for material cutting. The evaluation provided valuable insights into how the fabric responded under different cutting scenarios.

Seven samples were made in the following sizes:

Sample	Outer loop size	Inner loop size	Laser cutter settings	Amount cut
1	2x3cm,	1x2cm	Chiffon	x2
2	2x2cm	1x1.5cm	Chiffon	x2
3	3x4cm	0.5x2cm	Chiffon	x2
4	0.5x1cm	0x1cm	Chiffon	x2
5	2x1.5cm	0x1cm	Chiffon	x1 x1 fabric with 2cm slits down centre
6	3x4cm	1x2cm	Heavy Cotton	x2
7	3x4cm,	0x2cm	Heavy Cotton	x1 (hem test)

Table 29: Hand-linking samples 1-7.

Results: Although the method itself showed promise, the lightweight nature of the commercial casein twill proved unsuitable for this type of design as it was challenging to create a rigid structure. The casein twill also tends to fray making it difficult to achieve a neat finish. It was hoped that by using the laser cutter, the heat from the laser would help to seal the edges of the fabric to help this issue. The 'Chiffon' cutting settings did not cut all the way through the fabric which still frayed upon removal from the cutting bed. The 'Calico (heavy)' setting provided a much more efficient cut through leaving a cleaner line that was easier to remove from the cutting bed without fraying. Some visible singeing occurred on the edges of the cut lines; however, this was the desired outcome to help control fraying.

Regarding the size and shape of the loops, longer and broader loops (samples 1, 2, 3, and 6) resulted in a messy appearance. In comparison, shorter and thinner loops (samples 4 and 5) created a tighter, decorative effect. The linking of loops created a ruched look down the centre join, which could be utilised to shape waistlines, cuffs, or garment seams.

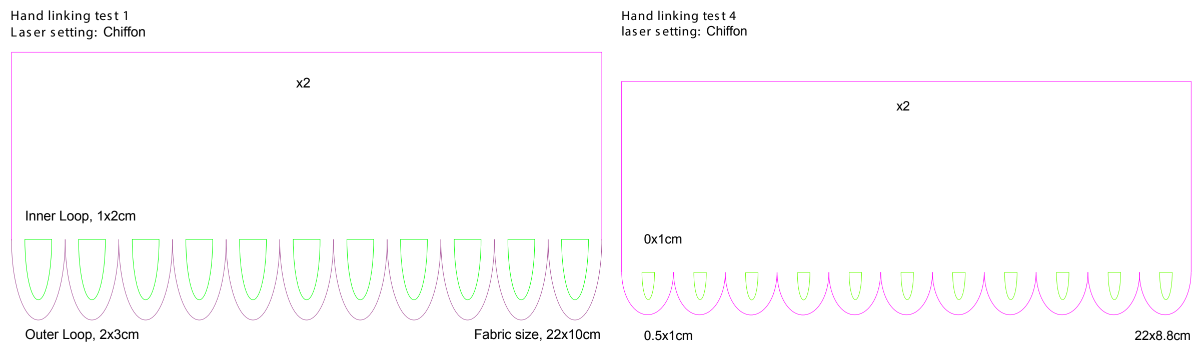


Figure 161: Cutting pattern from samples 1 and 4 demonstrating the shape and placement of loops.

Different placements of loops were tested in addition to regular joins on the fabric edges. For instance, sample 5 linked loops to the centre of a second piece of fabric to create a gathered peplum effect, and sample 7 tested loops to create a hem along the fabric edge. Material samples were tested and pinned onto the mannequin to explore how the shaping works against different areas of the body. By experimenting with the placement of loops along the fabric's centre, shaping possibilities for waistlines and sleeve cuffs were discovered.

After developing a small range of material trials, a dress was drafted in Adobe Illustrator using a basic dress block for laser cutting. The pattern featured rows of 2x1.5 cm loops (0x1cm inner slit) down the sides and across the shoulders to join the front and back together. However, the loose, shift style of the dress combined with the thin casein twill resulted in a lack of shape and an unflattering fit on the mannequin. All shaping around the armhole was lost as the looped side seam pulled the fabric down, resulting in a loose-fit, tank-style trapeze dress.

Reflection: The method of hand-linking fabric showed potential in creating shape and adding decorative effects within garments. However, the main setback faced in this experiment was the choice of the commercial casein twill, which proved thin and flimsy, making it challenging to achieve any kind of structure. For future experiments, using a heavier or sturdier fabric, such as organza or non-woven material like those used in paper dresses, would likely provide a better finish and retain shape, especially in areas like the armholes.

Reflecting on the woven monofilament samples developed in Section 5.4.4, it becomes evident that these materials would be much better suited for this type of garment sampling compared to the commercial casein twill. The stiffer nature, increased weight, and wiry characteristics of the monofilament offer the potential to form more rigid structures and reduce the tendency to fray at the edges.

This design experiment was a valuable learning experience in assessing the challenges of using currently available casein materials and highlighted the importance of developing suitable fabrics for specific design approaches. Using a laser cutter proved to be an effective tool for precision cutting and controlling fraying; however, this requires additional energy consumption compared to hand cutting. Further exploration of loop sizes, shapes, and placements would expand understanding of how these elements contribute to the final garment's aesthetic and structure.

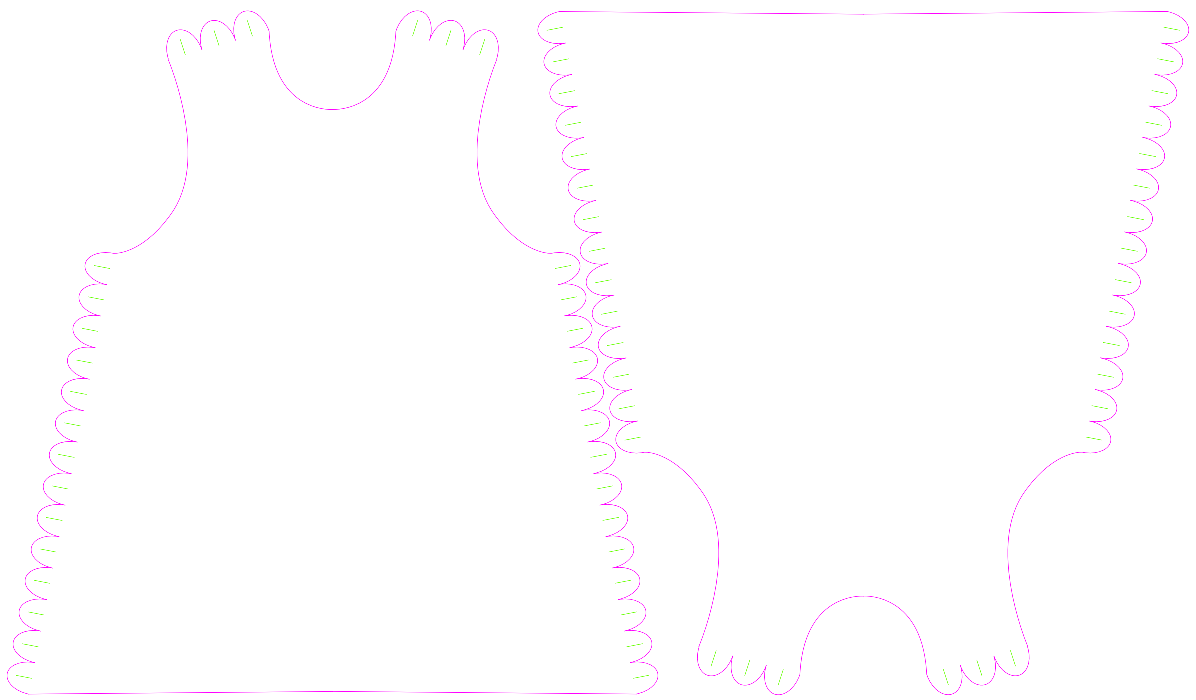


Figure 162: (Top left) Testing placements of sample 4 on the mannequin.
Figure 163: (Top Righ) Testing placements of sample 5 on the mannequin to create a peplum effect.
.Figure 164: (Bottom centre) Flat dress pattern drawn on Adobe Illustrator.

6.3.6. Ex 22: Hand Tying As A Method Of Garment Construction

Aim: Following experimentation with hand linking, fabric ties were explored as an alternative method of joining fabric, allowing for adjustable sizing and creative decorative effects. This experimentation aimed to find a more aesthetically pleasing way of joining fabric and creating shape without stitch.

Method: Two pieces of fabric were cut with 20cm slits, spaced 1 inch apart, allowing them to be tied together to form a join. This larger fabric sample was then pinned to the mannequin to explore various placements and effects.

Results: Images 165 - 167 showcase some of the placements that can be achieved using this fabric joining technique, resulting in a pleasant, gathered effect and shaping the garment nicely. Simple one- or two-piece garment patterns can be created using this method by cutting a large seam allowance to fringe and tie together. This approach offers adjustable sizing and enables various effects by choosing how tight or loose to tie the fringing or even leaving some areas untied (e.g., to create a side slit on a skirt or dress), providing an element of customisation. Overall, this method proved to be a quick and effective option for designing TCGs.

Figure 165 - 167: Testing placement of tie together seams on the mannequin.

Reflection: Tying the seams together in this way gave a better aesthetical finish than looping. Although the thin fabric still created issues, cutting basic strips (rather than loops) was easier to cut by hand, and fraying was less noticeable once tied. The row of bows gave an interesting finish and has the potential to be utilised in a range of placements such as side seams, centre back or centre front, as well as waistbands or more decorative placements and offers the opportunity to be easily untied/tied as a fastening or a more customisable look.

Depending on garment shape and the nature of the material used, all three techniques could be used in conjunction with each other, using ties/links for joins which require more strength, such as side seams, and glues for bottom hems, particularly on heavier garments where the glue doesn't show through. Although the results of this experimentation have been limited (due to the need to sample using commercial casein material), it has provided an excellent start to understanding both the design and material requirements when it comes to the development of TCGs, namely, the creation of a material with a certain level of stiffness and the ability to not fray.

In reference to the RELR framework (3.2.3, p72), each of the techniques explored so far offers a range of opportunities for efficiency and ease of recovery. Using casein glue, hand linking, and hand tying all require minimal skills and energy to make and apply and are reasonably simple to incorporate into traditional pattern cutting. Table 30 takes the criteria of the RELF framework and maps each against the three techniques.

Technique	Opportunities for Efficiency	Opportunities for Longevity	Opportunities for Recovery
-	Lean use of materials and energy	Lasts as long as required. Lean repair/maintenance Has multiple functions	Lean release of energy and material at end of life
Casein Glue	No additional materials or equipment required (glue can be made in lab alongside dope preparation). Low energy/skill required.	Creates a weaker bond than sewing – better for use of single wear items or as a method of finishing/hemming over joining.	Fully compostable, no separation of materials required.
Hand linking	No additional materials required. Laser cutting is preferred method of cutting which requires additional equipment and energy usage.	Creates a strong bond for joining fabric which is easy to put together/undo if necessary. Option of different effects and placements on the garment.	Fully compostable, no separation of materials required.
Hand Tying	No additional materials or equipment required. Larger seams allowance for fringing requires more material than other techniques	Creates the strongest bond for joining fabric allowing increased number of wears without compromising compostability. More opportunities for customisation and size alterations.	Fully compostable, no separation of materials required.

Table 30: Material technique mapped against opportunities for efficiency, Longevity and Recovery.

6.3.7 Ex 23: Tie Together Top

Aim: Following the development of no-sew methods of construction, the method of hand tying has been taken forward. This experiment aims to utilise hand tying within the design and construction of a basic top.

Method: This exploration of shape and pattern-cutting techniques offers valuable insights into creating minimalistic yet striking garments. Drawing inspiration from diverse sources, designers can implement various methods to achieve innovative and aesthetically pleasing designs. The trials conducted on basic garments lay the foundation for the development of TCGs with unique features allowing for easy manufacture and quick disintegration.

During the exhibition 'Balenciaga's Shaping Fashion' at the V&A (2017), print-out paper patterns of Balenciaga's 'one seam coat' were offered to visitors, allowing them to experience the construction of this coat for themselves. A copy of this printout was sourced online (Balenciaga One Seam Coat Pattern. 2017) and used as a template to create a range of clothing patterns which could be explored in paper format before transitioning to fabric. (Also see Section 6.3.9 for coat design.)

The coat is constructed by cutting the outer rectangle (line 1) and the larger dashed lines (line 2), then folding across the dotted lines (3 & 4). A red circle has been drawn over the pattern to indicate a neckline along with an additional red dashed line, which also needs to be cut, as this folds over to become part of the centre front of the coat. Line 4 defines the shoulders and sleeves, line 3 represents the side seams, and line 2 corresponds to the underarms.

Multiple adaptations of the A4 paper pattern were devised to explore various design possibilities representing a simple top, dress, and skirt. Each iteration sought to manipulate the 'one seam' placement to generate multiple shapes while incorporating a 17cm seam allowance for tie-together seams.

Results: This design originated as a shift dress but was transformed into a short-sleeved top by positioning the seam across the back, leaving the centre back open. After exploring several adaptations of the paper pattern, a to-scale version was drawn up in Illustrator and laser cut in casein twill. For the design demonstrated in figures 170 -171, the paper pattern was shortened, and the shoulder seam was cut to create the back ties, leaving a shorter, batwing-style sleeve.

Reflection: This design was much more effective than the initial shift dress trial with looped side seams (6.3.4). The shape of the top fit the mannequin better and looked more like a traditional batwing t-shirt shape from the front. The tie detail across the back gave a decorative aesthetic and created a subtle gather, shaping the top around the bust while offering a loose and comfortable fit. Although ties could also be added to the centre back to close the gap, too many ties could look overcrowded and fussy. Keeping the back open suggests a more contemporary style whilst using less additional material.

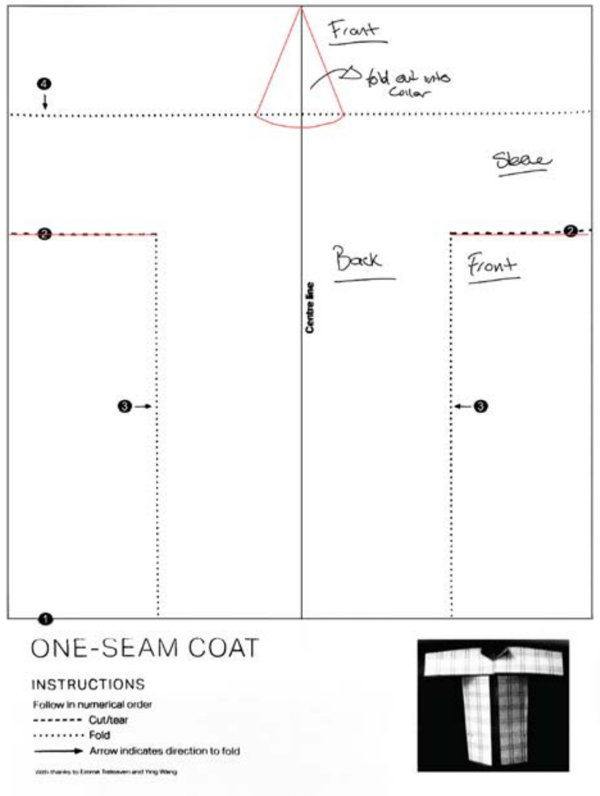


Figure 168: Balenciaga One-Seam Coat instructions (2017). Edited.

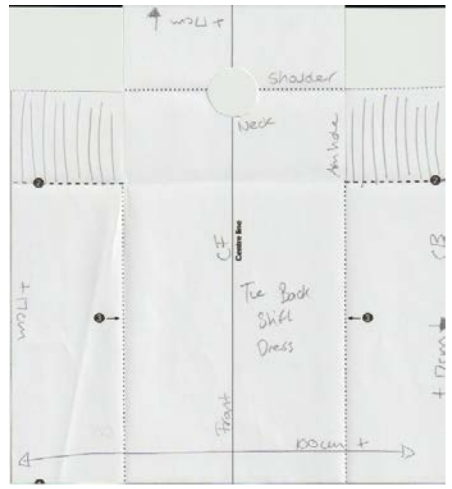


Figure 169: Miniature paper pattern of the tie-together top.

Figure 170: Tie-together top toile (side).

Figure 171: Tie-together top toile (back).

6.3.8 Ex 24: Tie Together Skirt

Aim: The goal of this experiment is to utilise hand tying within the design and construction of a basic skirt.

Method: To create the seam, one piece of fabric was cut with fringing on either side (17cm long, 1 inch apart). This technique also creates an opening for getting in/out of the garment without needing a zip or buttons.

Results: As with the tie-together top, the tie sides allow for adjustable sizing and style of the skirt. Different variations in the skirt in terms of length could easily be created. For example, a longer skirt design allows some fringing to be left untied to create a side split. The look of the garment would be appropriate for several different styles, such as a beach skirt or an evening/party look.

Figure 172: Tie-together skirt toile (front).

Figure 173: Tie-together skirt toile (side).

Several iterations of the skirt and the tie-together top were drafted on Adobe Illustrator, exploring potential lengths, shapes and styles utilising this technique. As with transitional pattern drafting, once a block shape or template is created, this can easily be adapted for a range of new designs.

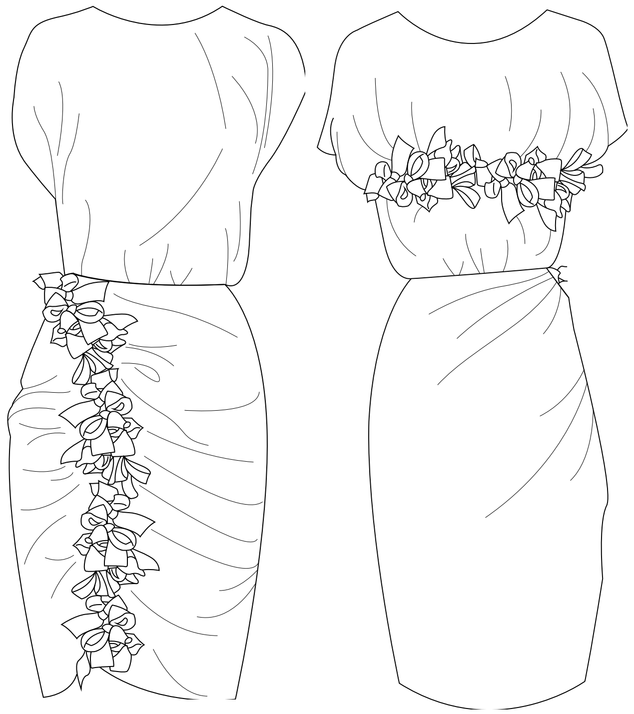


Figure 174: Digital sketch of a tie together top and skirt outfit. (Mini skirt and T-shirt.)

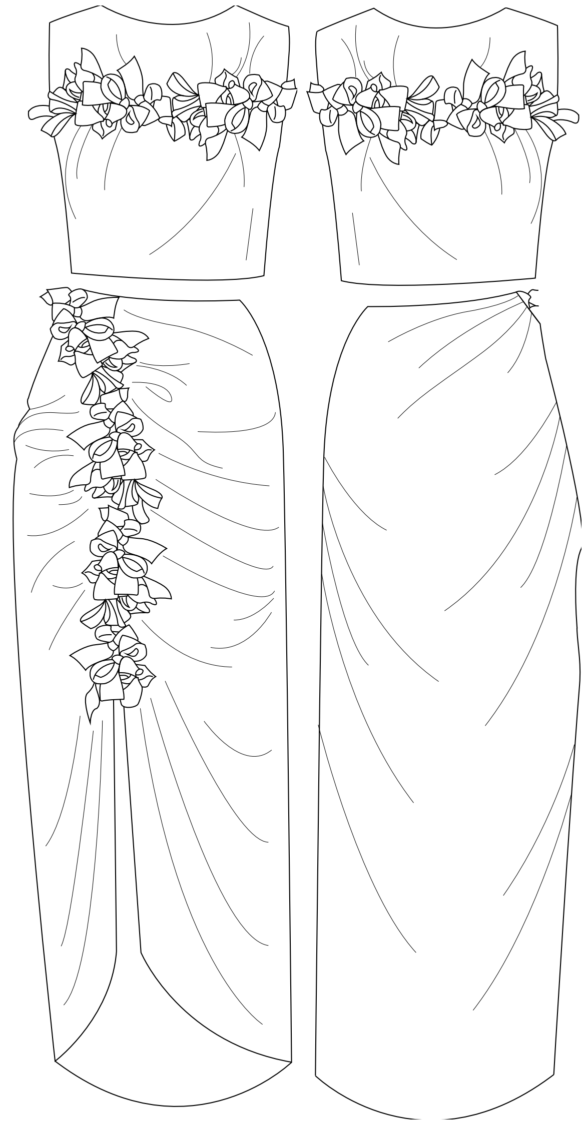


Figure 175: Digital sketch of a tie together top and skirt outfit. (Midi skirt and sleeveless top.)

Reflection: Despite using a simple, 1-piece pattern, the skirt provided a great deal of shape and was easy to adjust in size and appearance. Simple adaptations such as twisting the side seam (ties) towards the front gave a more interesting look that the wearer could manipulate. The ruching caused by the ties pulls the opening of the skirt upwards, creating a flattering curved bottom hem and helping give the skirt its fitted shape around the hips.

6.3.9 Ex 25: Tie Together Dress

Aim: This experiment uses hand tying within the design and construction of a basic dress.

Method: Several dresses were initially toiled, placing the ties in various ways across the body.

Results: The example demonstrated in Figures 176 - 177 shows a two-piece dress pattern with ties across the shoulders and along two slanted side seams to create a twisted effect. Tying the ties looser or tighter gives the dress different looks, which can be lengthened or shortened at the shoulder and side seams depending on the desired style. This pattern-cutting method opens possibilities for various garment styles, which can be as straightforward or as complex as desired. The designs sampled here are very basic and consist of one- or two-piece patterns; however, more complex structures could be established with various panels to create different shapes and a fuller design. Of course, the more panels added, the more fabric, time, and energy required, both for manufacture and degradation.

Reflection: Although methods of pattern cutting and creating seams have been established, the issue of finishing the garments still stands. As this existing casein material is highly prone to fraying, leaving a raw edge around necklines, armholes, and other edges looks unpleasant and unfinished. As a solution, this is where paper dresses often employ bias bindings and tapes (p217); however, this introduces new materials and requires sewing.

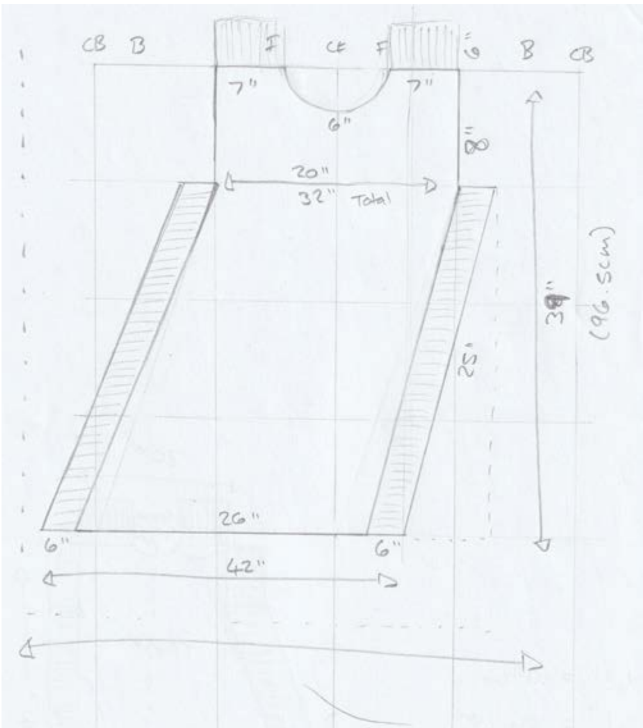
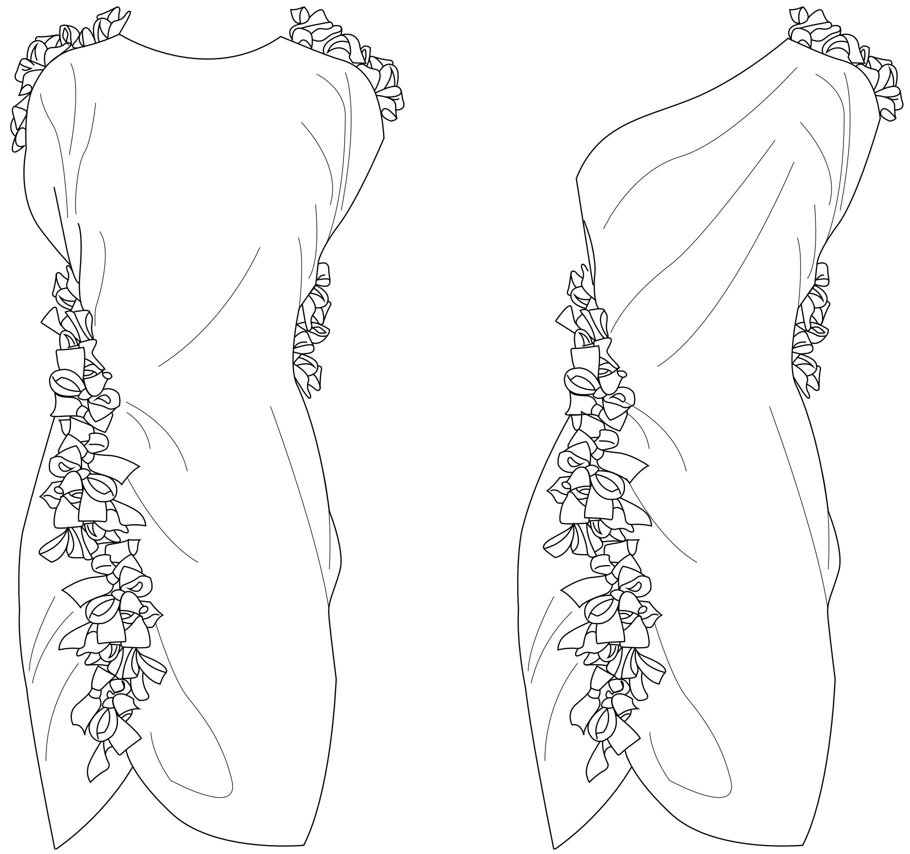


Figure 176: (This page) Rough sketch of dress pattern

Figure 177: (Next page, top) Digital sketches of the tie together Dress.

Figure 178: (Next page, bottom) Tie together dress toile.



6.3.10 Ex 26: Tie Together Coat

Aim: After designing an initial range of techniques suitable for TCGs using the available casein twill as a starting point, the next stage was to explore a garment ideal to a heavier weight of fabric utilising the woven materials developed in Ex 12. This experiment aims to use hand-tying within the design and construction of a basic coat.

Method: As visited in section 6.3.2, Balenciaga's one-seam coat was the starting point for this design process.

Several coat versions were toiled in a medium-weight calico before a simple, tie-together, two-piece design was decided on. Figure 179 shows how the original pattern was adapted to create the new coat design. The top and bottom halves of the coat were split into two pieces, and fringing was added across the entire seam, which allowed the pieces to be tied across the back and under the arms, as demonstrated in the illustration below. A full-scale, half-toil was hand-cut to test the fit and structure (Figures 180 - 181).

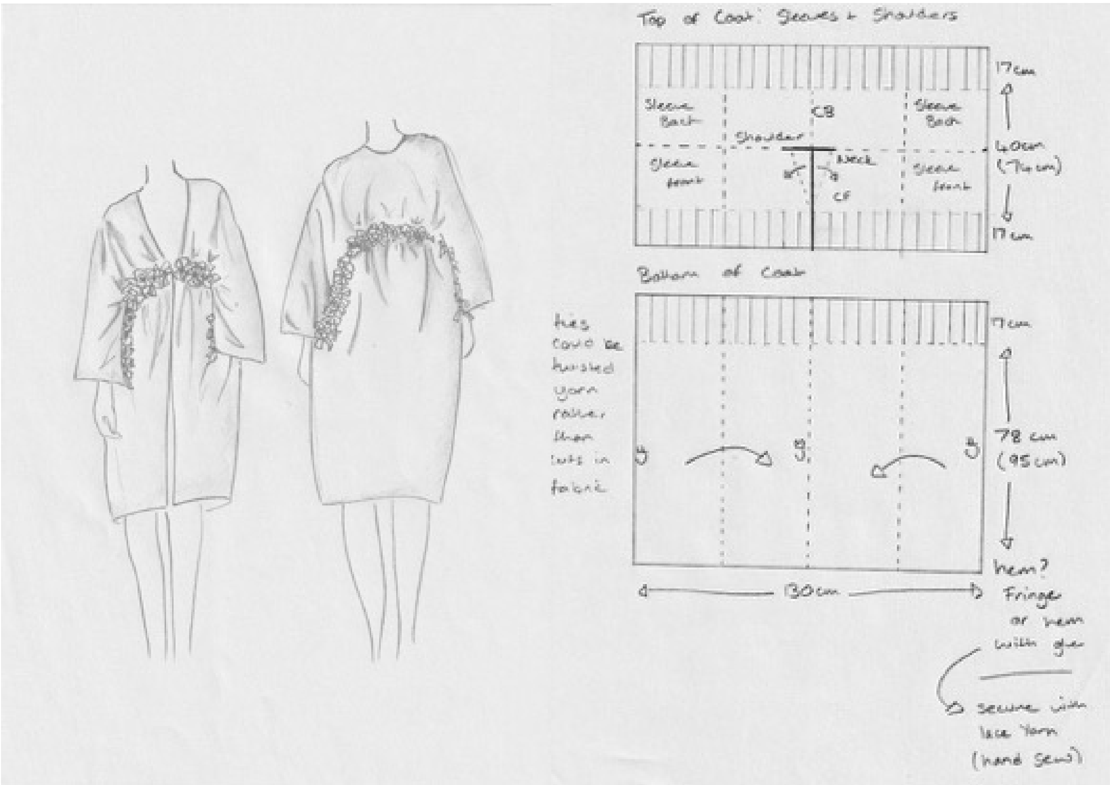


Figure 179: Sketch of tie together coat and coat pattern

Results: The resulting coat had a kimono-like appearance with a loose, cocoon shape and batwing sleeve. Ultimately, the design was very simple, giving way to the decorative finish of bows running through the centre of the coat. A loose-fitting design such as this could be offered in a smaller size range, such as a S/M and a M/L, meaning smaller production runs are possible. The design lends itself well to various materials and weights depending on season. Although it has been designed with the commercial casein fabrics in mind, stiffer or light-weight materials such as organza (more closely represented by the casein monofilament) could also be explored.

Regarding components, the coat is designed without fastenings such as buttons and is designed to be worn open. Alternatively, the centre front ties could be used as a fastening if desired. The coat is unlined and toiled in a medium, above-the-knee length. Depending on how the coat is finished, this could offer an opportunity for customisation, allowing the consumer to cut the coat to the desired length upon purchase. Although the toil is unfinished, edges such as the centre front, neckline and hem could be glued in place or features such as fringing could be used to finish areas, including the bottom hem or sleeves.

Figure 180: Tie together coat toile (front).

Figure 181: Tie together coat toile (side).

6.4 Transient, Casein-Based Garments

The concluding section of this chapter connects the theoretical foundation with tangible design applications, delving into an array of digital fashion illustrations and 2D patterns crafted using Adobe Illustrator and Photoshop. The purpose of this exercise within the broader context of this thesis is to embody the culmination of design work and practice-based research investigated across Chapters 4 and 5, blending decorative methods and mono-material construction techniques with weaving outputs from Experiments 12 and 16.

2D patterns have been used to help visualise the design and manufacturing process. However, it is essential to note that these patterns are not drawn to scale and serve as an illustrative tool conveying the shapes and material quantities required in creating such garments.

Each look/outfit has been designed as evening or partywear with a maximum lifespan of 6 months.

6.4.1 Garment Collection: Looks 1-4

This initial collection of garments was curated with the lab-produced monofilament in focus. This material imparts a more rigid texture to the commercial casein fabric while retaining its soft and lightweight tactile quality. This distinctive blend renders it an ideal candidate for crafting garments with more structure, representing the properties of paper dresses in a typical shift dress or A-line shape. Screen-printing was used as an additional decorative technique, utilising the design work into avocado inks in Ex 8.

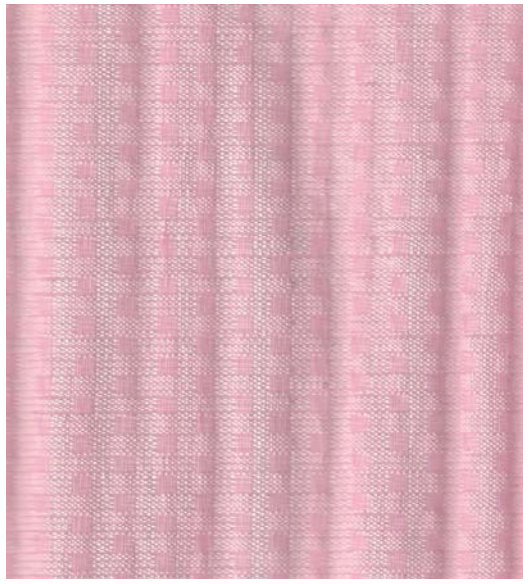





Figure 182: (Top right) Monofilament woven Sampe 1.
Figure 183: (Top left) Monofilament woven Sampe 2.
Figure 184: (Centre right) Monofilament woven Sampe 3.
Figure 185: (Centre left) Monofilament woven Sampe 4.
Figure 186: (Bottom right) Screen-printed floral design.
Figure 187: (Bottom left) Screen-printing floral motif.

Look 1

Design notes: This asymmetric dress design was adapted from the toile in Ex 25. The curved sides give it its twisted effect, while the tie-together finish provides a ruched look, shaping the bottom hem and pulling the material towards the centre. This dress has been designed using monofilament sample 1, which features a soft, checkered look in a dark pink colour and has been screen printed using a large floral design in avocado ink.

As this material does not appear to fray easily, the dress's bottom hem, neckline and armholes are designed to be left as a raw edge. Ties around the waist/underarm can be untied, allowing access into the garment and can be loosened/tightened for the desired fit.

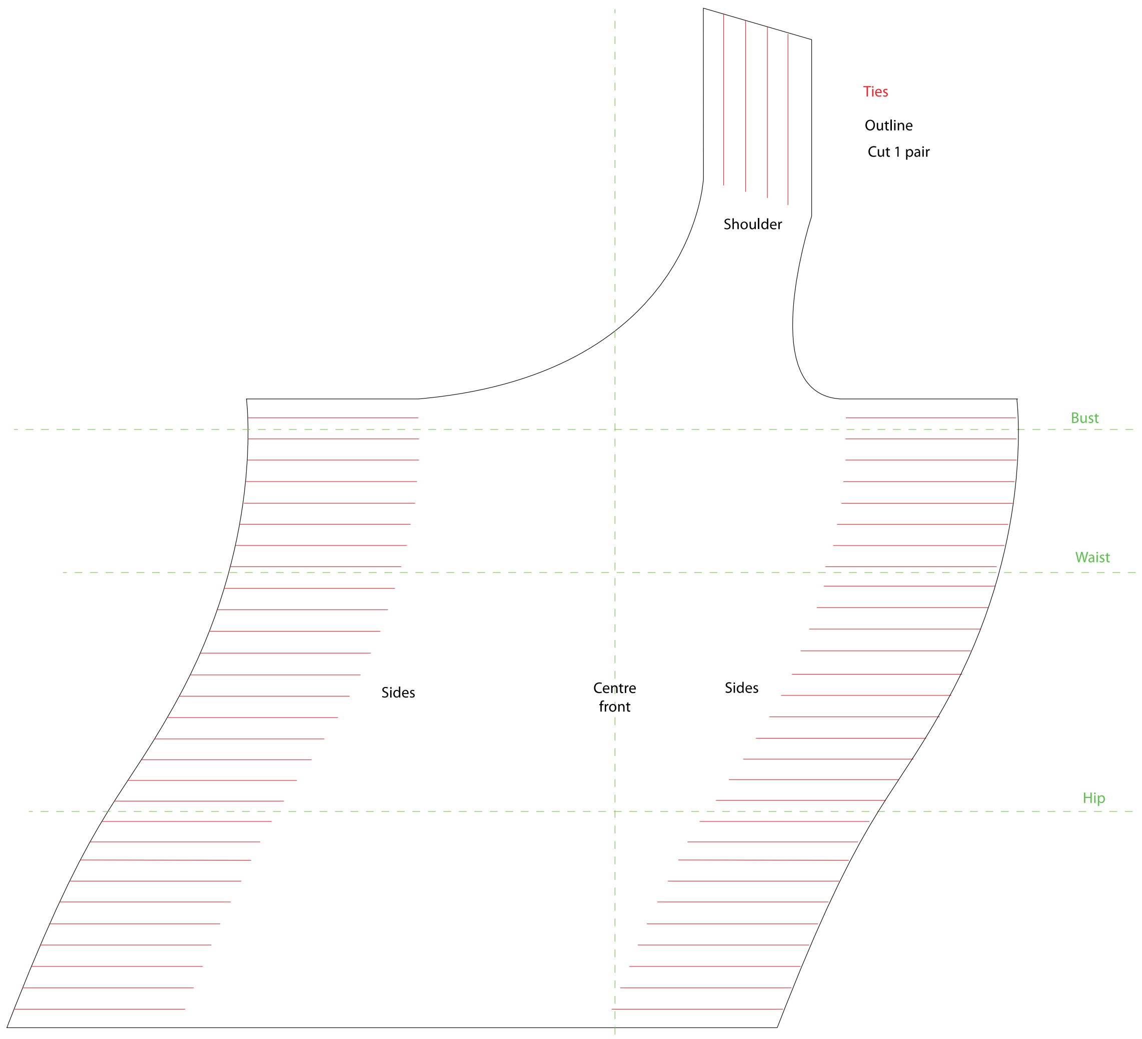


Figure 188: Look 1 digital pattern (not to scale).

Figure 189: Look 1 digital illustration.

Look 2:

Design notes: This asymmetric top and midi skirt combo was adapted from the toiles in Ex 24 and Ex 25. The skirt is cut on the fold in one piece and has a series of ties at the top in a curved shape to give the skirt a fitted look with a large side split. The asymmetric top features ties on the shoulder and corresponding side seam, while the other side seam is glued together, giving it a sleeker finish. As with the asymmetric dress, the bottom hem, armholes and neckline are designed to be left raw.

The top and skirt have been designed using monofilament sample 2, which features a contrasting white and pink stripe, utilising both BCP dyed and unded monofilaments. Further alterations could include various lengths and tie placements to reduce or remove the side split.

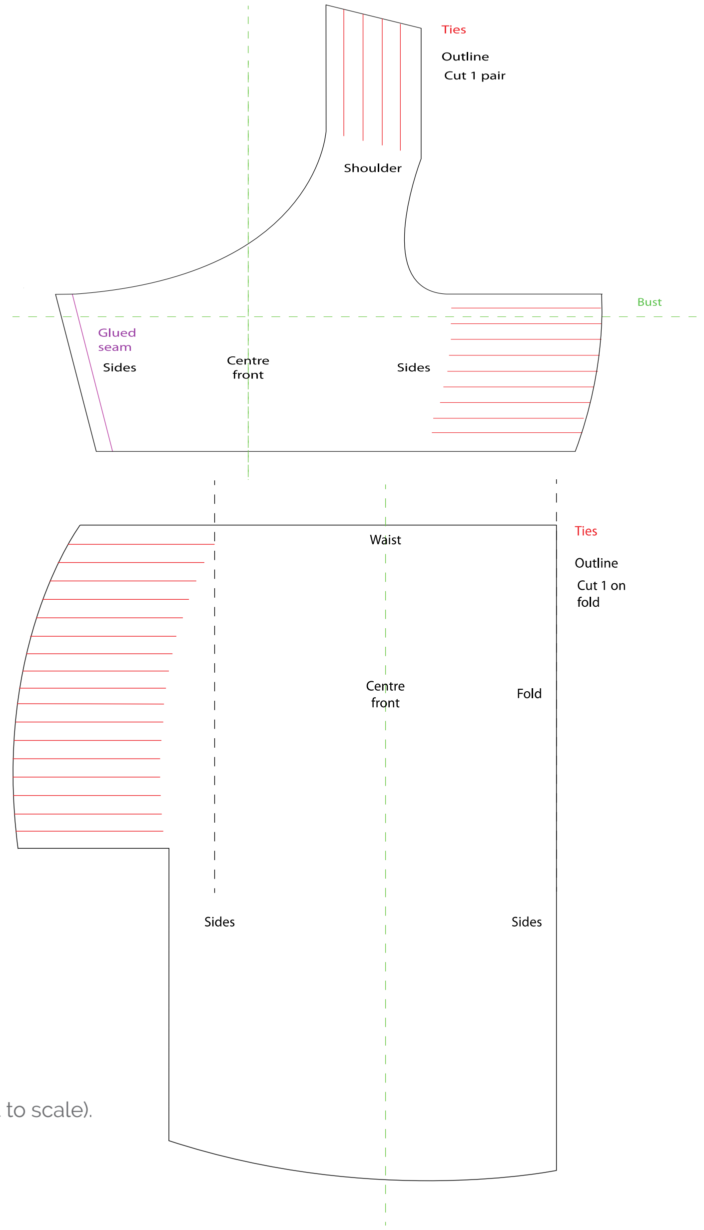


Figure 190: Look 2 digital pattern (not to scale).

Figure 191: Look 2 digital illustration.

Look 3:

Design notes: This look utilises the ruched midi skirt in monofilament sample 2.

The top design was adapted from Ex 23 by continuing the ties around the front bust and slimming the shoulders to create a tank top style. The top is cut in two pieces; the material folds over the shoulders and ties around the entire bust, creating a slimmer, gathered style. The neck is designed to be large enough to fit over the head without requiring a fastening. The top is designed using monofilament sample 4 (BCP dyed monofilament).

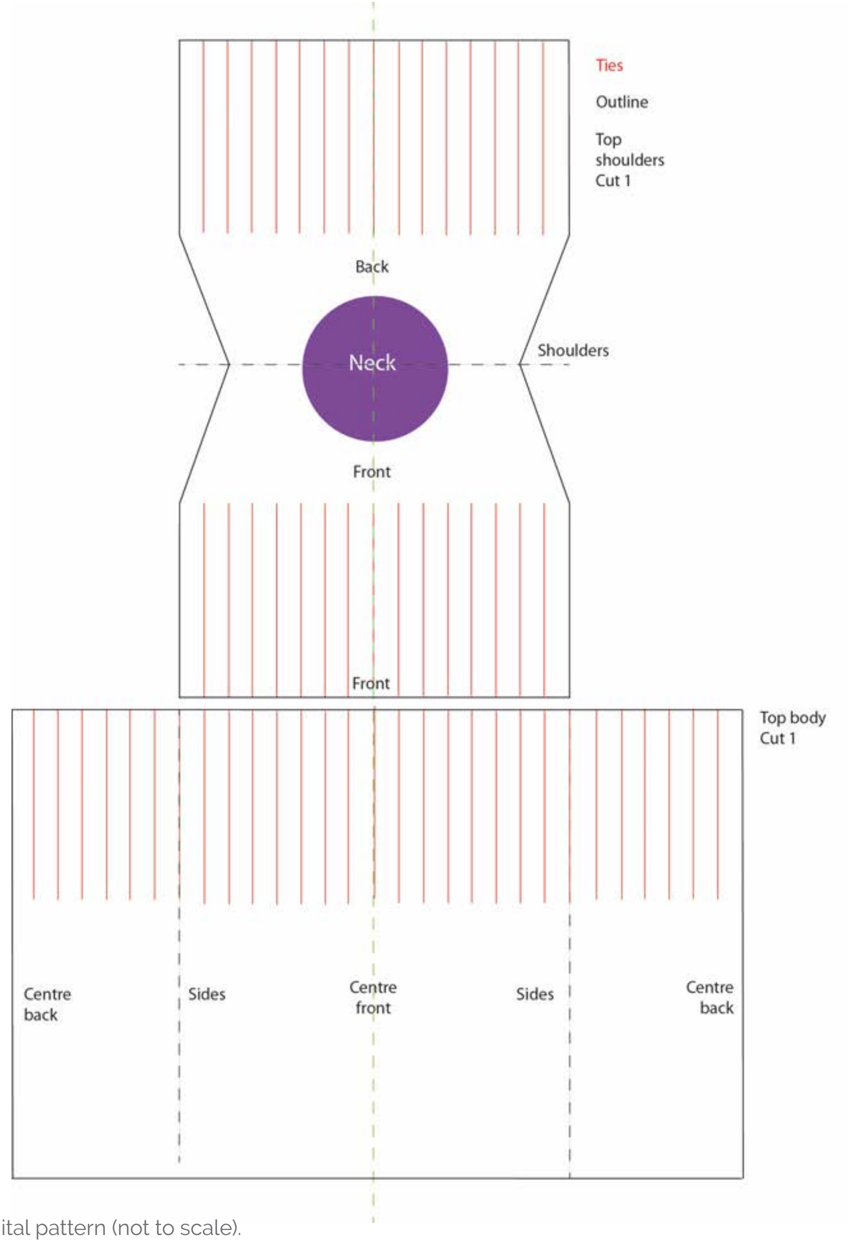


Figure 192: Look 3 digital pattern (not to scale).

Figure 193: Look 3 digital illustration.

Look 4: Double Panel Midi Dress

Design notes: This dress design exemplifies a more complex example of a tie-together garment. The double-panel midi dress was adapted from Ex 25, combining looks 1 and 4 by adding an additional panel to the back and front of the dress. This would create a more extreme gathered effect down the dress, pulling material towards the waist for a fitted look. As with the ruched midi skirt, the ties stop below the hip, creating a side split and deep curve on the hem. The ties are positioned in a more extreme curve from the shoulder seam to create a twisted look following the body's contours.

The dress is cut into six pieces and glued down the side and shoulder seams. The bottom hem, armholes and neckline are designed to be left raw. The dress is designed using monofilament sample 3 (undyed monofilament).

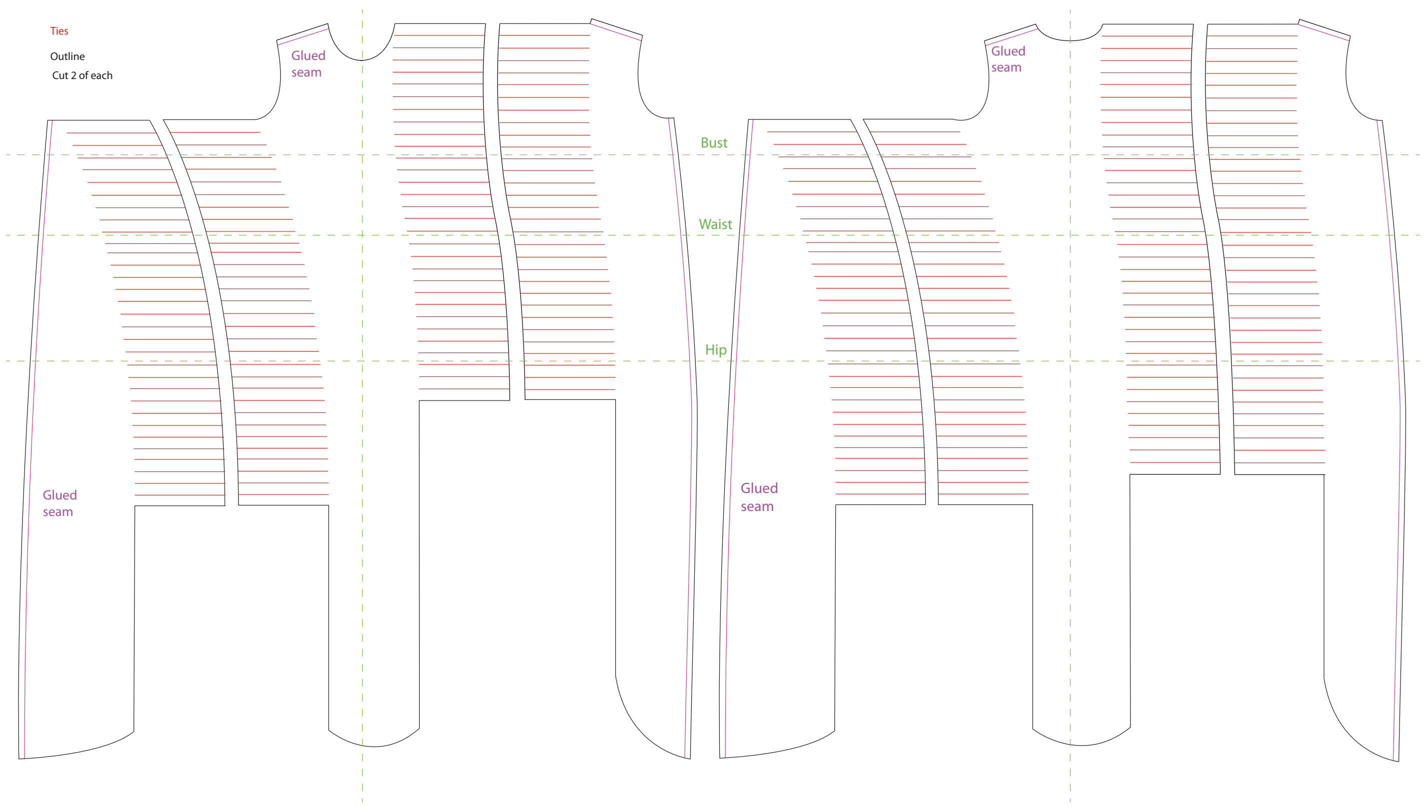


Figure 194: Look 4 digital pattern (not to scale).

Figure 195: Look 4 digital illustration.

6.4.2 Transient, Casein-Based Coat: Looks 5-8

The casein-based coat captures an assortment of iterations stemming from a singular design. The creative process utilises the final array of commercially woven samples to visualise each woven structure in garment form.

Additional decorative features such as screen-printing were considered; however, the design of the woven fabrics offered enough versatility in colour and pattern. The bulkier, textured nature of the woven materials would have also made it more challenging to achieve a solid print.

The coat has been designed as evening or daywear with a maximum lifespan of 1 year. It features a boxy kimono shape and a ¾ sleeve.

The pattern demonstrated in Figure 196 is utilised across looks 5-8.

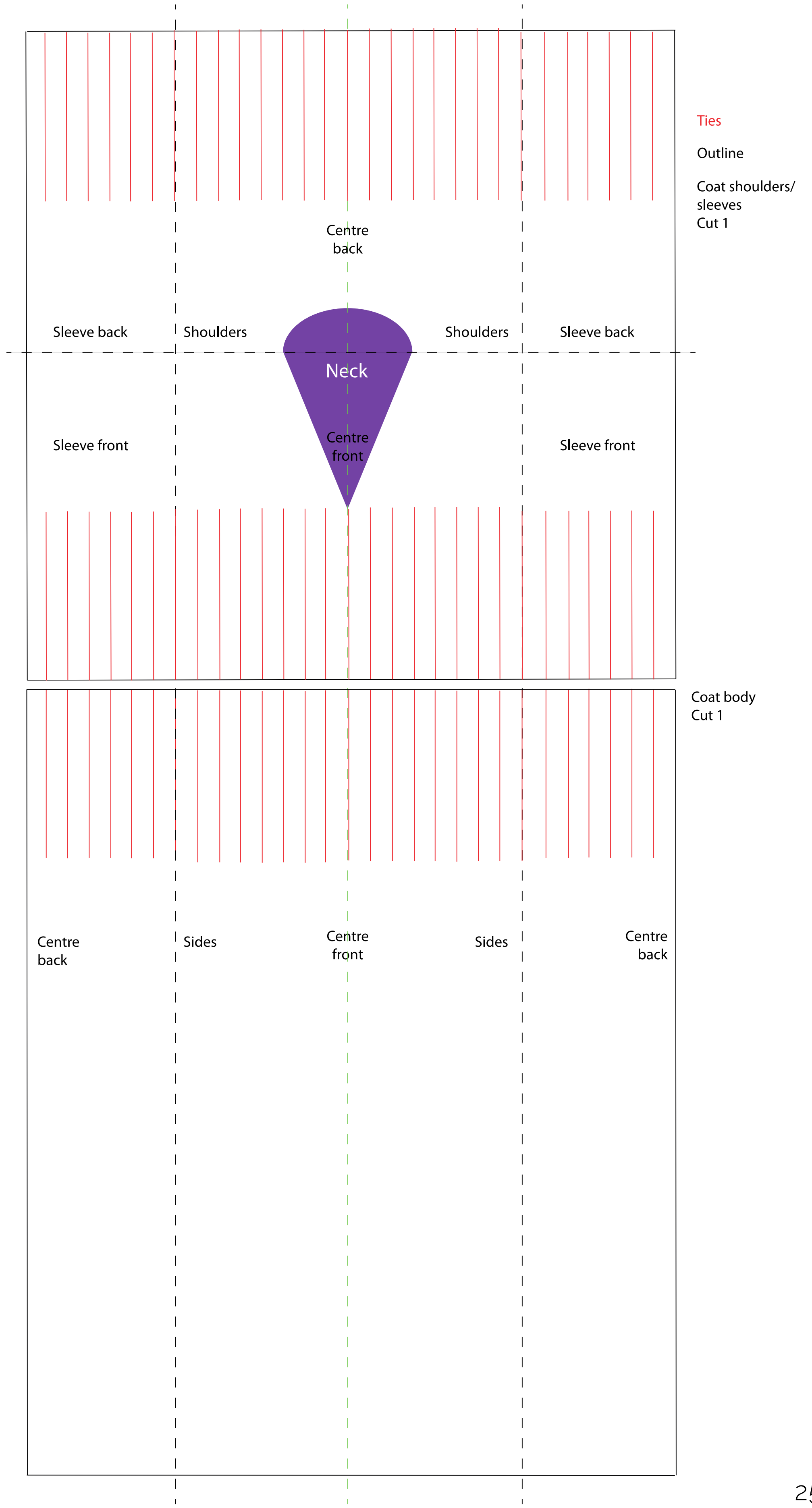


Figure 196: Tie together coat digital pattern (not to scale).

Look 5

Design notes: This coat utilises woven sample 1 in a pick-and-pick weave pattern using varied weights of avocado dyed and undyed yarns. The various weights of yarns used provide a slightly raised yet smooth surface in a soft, heavier material with a glossy sheen. The fringing around the hem uses heavier-weight yarns in cream and pink for a fuller fringe. The neckline and sleeves are turned under once and finished with casein glue.

Figure 197: Look 5 digital illustration and woven sample 1.

Look 6

Design notes: This coat utilises woven sample 2 in a herringbone weave pattern using onion dyed and undyed lace-weight yarns. The matching weights of yarns used provide a flat, smooth surface and medium-weight material with a glossy sheen. The coat is designed to be finished with fringing on the bottom hem (created on the loom using the original warp). The neckline and sleeves are turned under once and finished with casein glue.

Figure 198: Look 6 digital illustration and woven sample 2.

Look 7

Design notes: This coat utilises woven sample 3 in a pick-and-pick, diamond weave pattern using avocado dyed and undyed yarns in varied weights. The various weights of yarns used provide a slightly raised surface in a soft, heavier material with a glossy sheen. The coat is designed to be finished with a lightweight fringing on the bottom hem (created on the loom using the original warp). The neckline and sleeves are turned under once and finished with casein glue.

Figure 199: Look 7 digital illustration and woven sample.

Look 8

Design notes: This coat utilises woven sample 6 in a diamond weave pattern using onion dyed and undyed lace-weight yarns. The matching weights of yarns used provide a smooth surface and medium-weight material with a glossy sheen. The coat is designed to be finished with fringing on the bottom hem (created on the loom using the original warp). The neckline and sleeves are turned under once and finished with casein glue.

Figure 200: Look 8 digital illustration and woven sample.

6.4.3 Answering The Brief

Garments have been designed to produce as little waste as possible through both cutting techniques (pre-consumer) and compostability (post-consumer). The 2D patterns developed are simple shapes containing minimal pieces while eliminating small and awkward elements such as pockets, plackets, collars, cuffs, etc. Garments are also designed to be unlined, taking advantage of casein's soft, hypoallergenic properties as a raw material and textile fibre.

Upon disposal, garments would ideally be disassembled (untied) and cut into small pieces to aid the composting process. With no zips, buttons, or stitched seams, this becomes a quick and easy process which can be done by the consumer or upon return to the manufacturer/retailer.

If these designs were to be taken forward and toiled in the corresponding material, it would be ideal to conduct thermophilic and plant-response testing on a basic dress and coat design utilising a similar methodology to that used in Ex 18 and Ex 19. This would involve recording the initial weight of the garment and how long it takes to fully disintegrate in a compost matrix. If a basic dress (such as look 1) did not disintegrate within the 90-day criteria, changes to the design would be required to reduce the overall weight of the dress.

In terms of manufacturing, garments are simple and quick to make with a low level of skill or knowledge of garment construction required. Depending on the methods used and the scale of production, manufacturing such garments has the potential to be a low-energy process due to the lack of required machinery such as sewing machines.

One acknowledgement is the contrast in material consumption between traditional garments and speculative TCGs. This divergence showcased through the larger seam allowance for the ties, is an intentional choice to embrace the no-sew element of the garments. Furthermore, the various construction techniques employed, such as hand-tying and glueing, can evolve into a broader repertoire of no-sew construction methods which ultimately aid in reducing overall fabric consumption.

Figure 201: Close up of commercial casein fabric ties.

6.5 Summary

The fast fashion industry can take significant strides towards sustainability and environmental responsibility by embracing a mono-material and regenerative approach. Alongside designing and creating physical garments, this chapter has explored the industrial system in which TCGs could exist. This system relies on waste collection/take-back schemes between government, industry, and consumer so that value can be recaptured locally at various points. Through respect for raw materials and acknowledgement of living system principles, this holistic paradigm encourages responsible actions throughout the garment lifecycle, allowing multiple opportunities for innovation.

Combining the principles of simultaneous design and RELR, textile and garment features have been considered in parallel allowing for maximum efficiency and recovery during manufacture and end of life. Designing garments in this way not only allows for flexibility in terms of print or surface design but can be used to create garments with a specific lifespan in mind, with the potential for resource recovery and regeneration built into their design from the start. From a textile perspective, potential considerations for the design of no-sew garments include material weight and handle, weave structure, drape or stiffness and fraying of edges.

Working with the existing casein fabric was not ideal for the development of TCGs, but at the time of writing, no other milk-based fabrics could be found. The available fabric was much too thin and flimsy to achieve any kind of structure within the garments. It also creased and frayed easily, making it challenging to finish neatly without sewing. Although calico could have been used for the toiling of theoretical casein-based garments (as it was for the one-seam coat), I chose to use this material to fully understand the implications of working with commercially available casein fabric. The difficulties faced during this period were reflected upon and fed back to JH and HAG to influence the development of future casein filaments and woven textile materials.

The consideration of textile construction can play a huge part in the design of TCGs. Whereas typically, a pre-made fabric is selected to best fit a garment's aesthetic and performance requirements, working directly with textile developers to weave tailor-made solutions into materials is essential. Now that the ESR is complete and able to produce casein filaments in larger quantities, there is a great opportunity to continue developing both casein filaments and woven samples simultaneously.

Figure 202 shows the workflow model for taking action through design. Outputs from Chapter 5 are used to establish new garment design techniques, and learnings are fed back to collaborators (JH & HAG) for future research. Again, the vision has been central to simultaneously steering the practice and theoretical research, ensuring that design methods and techniques align with the RDF.

WORKFLOW MODEL FOR TAKING ACTION THROUGH REGENERATIVE DESIGN

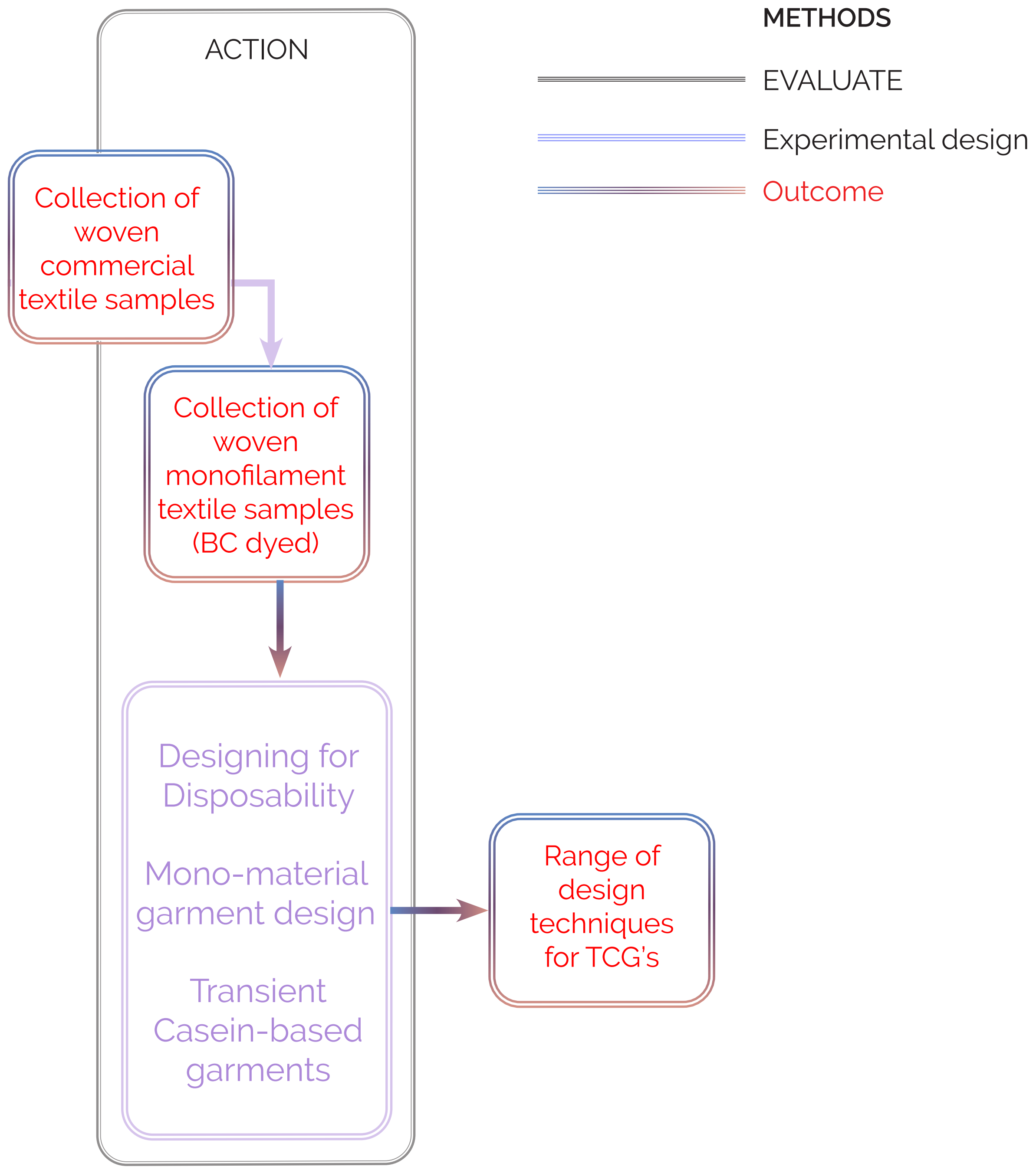


Figure 202: Workflow odel for taking action through Regenerative Design.

7

ANSWERING THE RESEARCH QUESTION

This research explored how textile practices can inform the development of casein-based materials from food waste for a regenerative fashion economy. A regenerative lifecycle for casein-based materials and garments was examined through practice-based research and experimentation, from raw material extraction to product creation and eventual composting.

This chapter serves as a reflective overview of how the outcomes of the objectives employed have answered the research question:

> ***"How can transdisciplinary collaboration between green chemistry and textile practices advance the understanding and utilisation of casein-based materials in regenerative fashion while challenging prevailing notions of disposability as an indicator of quality?"***

To answer the research question, four crucial data types were analysed: historical, societal, technical, and environmental, allowing a holistic investigation of the challenges and opportunities surrounding RPFs. This multifaceted approach has enabled a thorough examination of RPF utilisation within contemporary regenerative design whilst responding to the research question. For this chapter, the research question has been broken down into three key aspects to aid the reflective process:

- Transdisciplinary collaboration between designer and chemist (7.2)
- Utilisation of casein-based materials in regenerative fashion (7.1)
- Challenging prevailing notions of disposability as an indicator of quality (7.1)

7.1 Regenerative Design Framework

Regenerative design has emerged as a fundamental way of thinking throughout this thesis. By applying regenerative principles to casein-based materials and garments, this research has sought to create designs that not only minimise harm but actively contribute to ecological and societal well-being.

This section summarises the findings and central concepts explored regarding the RDF. Firstly, the evolution of casein-based materials and TCGs within the RDF, including their functional and aesthetic implications, is examined. Secondly, the ecological impact and important themes associated with TCGs are evaluated utilising the RDW introduced in Chapter 3.

7.1.1 Designing For Regenerative Speedcycles

Throughout this research, the initial focus on developing circular textile materials from casein for a quality fashion market underwent a significant transformation. While quality was an essential consideration at the project's outset, as the research progressed, the concept of quality was scrutinised and working with caseins' natural strengths and weaknesses became the priority. Within the RDF that underpins this research, the need to redefine our material requirements became abundantly clear. This process inspired an exciting opportunity to explore materials explicitly created for a short, transient lifecycle whilst addressing the need for quickly consumed garments.

Goldsworthy (2017: p.4) said, "We must stop viewing the product as the ultimate vehicle for longevity and start to see the materials themselves as holding the true value". Design is, therefore, challenged to retain this value at the point of disposal (Hall, 2021). This thesis defines value in terms of nutrition, which can replenish soil upon composting and is determined through the raw material and at the material processing stage. No matter how long a product is intended to last, design must facilitate the creation of pathways that ensure the availability of this nutrition upon disposal.

One of the significant ways this research has built upon Goldsworthy's original concept of speedcycles (Goldsworthy, 2017) is by contextualising it within the realm of regenerative design. While Goldsworthy's work provided the foundation, this thesis has expanded upon it by incorporating a deep understanding of casein as a raw material and its potential within the fashion industry. In doing so, the original concept has been redefined and enriched to include not only the rapidity of fashion cycles but also the regenerative and consumer-centric aspects of the design process.

Regenerative Systems Thinking

Within the RDF, many interconnected sites and approaches are envisioned to work harmoniously and be positioned within the broader context defined by Kate Raworth's concept of a social foundation and ecological ceiling (2017). Raworth emphasises the need to balance human needs with planetary boundaries, ensuring that economic activities do not overshoot ecological limits while fulfilling social foundations. This concept underscores that regenerative design should not only restore and renew natural systems but also address social equity and community resilience whilst providing a comprehensive lens through which regenerative design can be implemented.

In this regenerative approach, methodologies must find their place within the larger system encompassing all life on Earth. Regenerative design methods, in turn, become nested within transition design (representative of society and broader community needs), forming an integrated hierarchy of thought and action. This nesting extends to systems thinking techniques and design methods, which, in the end, produce results that prioritise the planet's inhabitants and well-being.

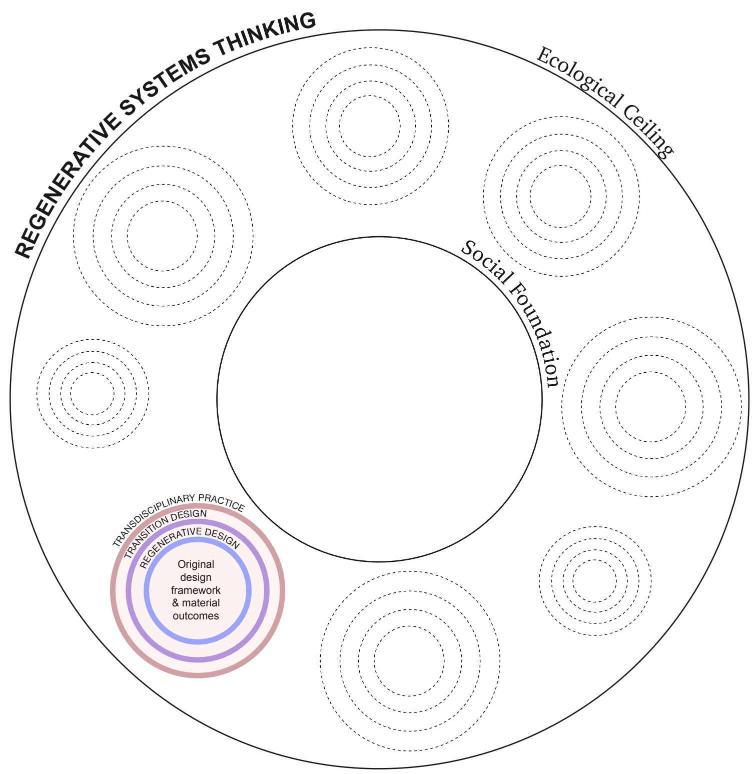


Figure 31 (revisited, p69): Transitioning from a garment design perspective to a regenerative system thinking perspective. (Adapted from McQuillan, 2020.)

As indicated by McQuillian (2020), the RDF necessitates that these changes should happen immediately instead of being reactionary to the standards and design processes that are currently in place in the FTI. Implementing mandatory and supportive laws is crucial to bringing about change in this situation (McQuillan, 2020). This aspect of the RDF serves as a foundation, offering broad context and constraints to guide decision-making. The configuration of each nested model varies based on technical, production, and design factors specific to the area of exploration. Nonetheless, they all share a common thread—boundaries defined by social and environmental considerations. Thus, the ecological and social impacts of the practices developed must be rigorously assessed, informing the design of outcomes that prioritise environmental and social well-being from the outermost perspective inward.

By incorporating Raworth's and McQuillan's principles, regenerative design becomes a dynamic component of a larger system that mitigates environmental damage and actively contributes to the health and sustainability of both ecological and social systems. This holistic approach ensures that design practices evolve to meet the pressing needs of the planet and its inhabitants, fostering a resilient and equitable future.

The Regenerative Design Wheel

The creation of products often results in a significant depletion of resources. Hence, academia and industry must collaborate to devise creative methods and tools to comprehend innovative design and production procedures that inevitably aid in eliminating waste and the use of virgin materials (McQuillan, 2020). To do so, the industry must reassess its approach towards the design of products.

The RDF emphasises the far-reaching effects of product design and production, urging designers to consider crucial issues such as stakeholders, supply chains, and critical impact areas. The use of the RDW has been instrumental in mapping the critical areas of the impact of casein through the design of both materials and garments. This systematic approach has allowed a comprehensive evaluation of the material's potential, environmental impact, and alignment with regenerative principles.

The RDW, which was developed in Chapter 3 as a part of the RDF (p73), has also served as a valuable tool for guiding collaborative design decisions and ensuring that they align with the overarching goals of the research, as well as identifying areas of opportunity for future research. Although the aim is to address these key areas holistically, the RDW allows users to view multiple chains between areas of impact, supply chain, stakeholders, and critical themes in isolation before drawing connections between problems and their potential solutions. Once this has been done, a systematic approach can be taken to detangling these issues and developing holistic solutions. Crucially, this approach encourages a deeper understanding of each critical theme regarding the very source of the problem and its long-reaching impact.

As demonstrated in Figure 32, the key themes addressed through the RDW during this research were water, soil, waste, and ecosystems. Although each of the eight themes has been considered and reflected upon at various points throughout the theory-based research, these four areas were directly investigated throughout the practice (Chapters 5 & 6). Figure 203 illustrates the chain in which these four themes have been considered, addressing stakeholders, supply chain and the overarching impact areas. By breaking each element down and viewing the lines of connection, we can identify overlapping solutions and areas for future research.

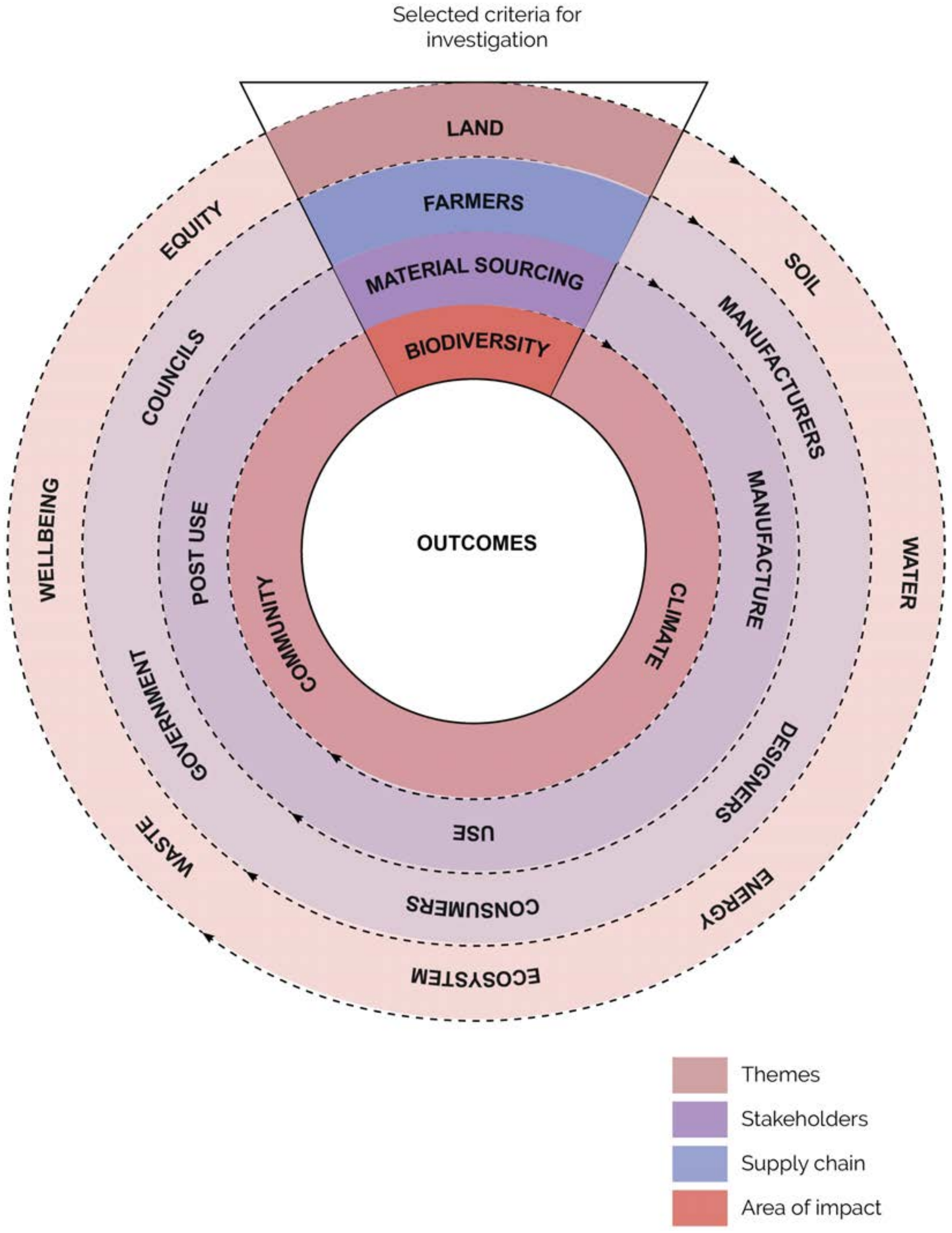


Figure 32 (revisited, p73): The regenerative design wheel is a tool for mapping key themes and areas of investigation against potential stakeholders, impacts and stages of the supply chain.

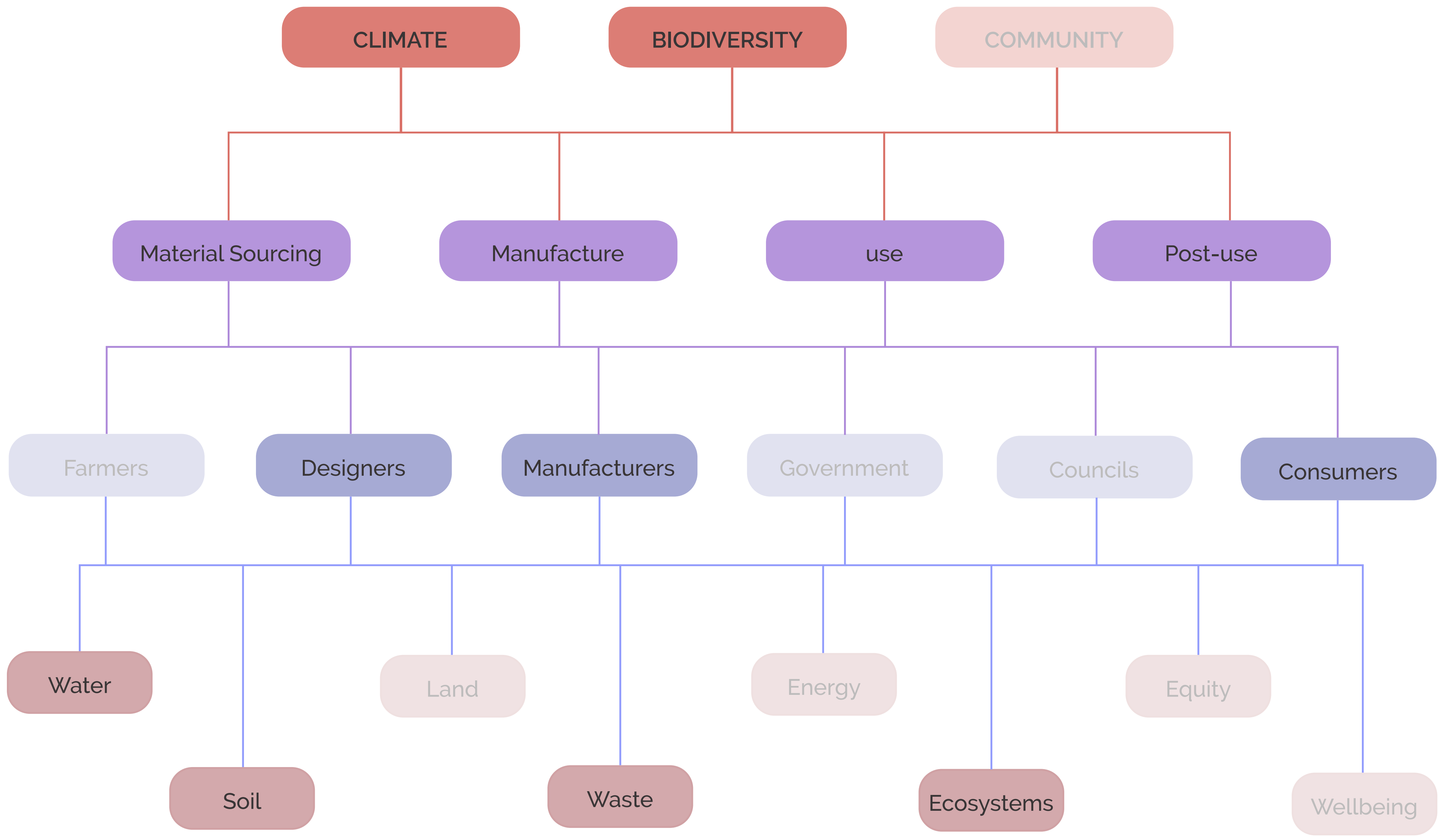


Figure 203: Mapping of which criteria has been addressed using the regenerative design wheel.

How each of the key themes has been addressed within this thesis is summarised below:

Water: The creation of casein-based materials in this research has aimed to positively affect aquatic life and habitats by reducing water usage through the supply chain and product lifecycle. This has been done by implementing a wet-spun dying process for casein fibres (Ex 15), eliminating the need for a separate dyeing stage further down the supply chain. Not only does this reduce water usage, but natural food waste dyestuffs (in this case, BCP) also ensure that any wastewater from this process is safe and non-toxic. Regarding TCGs, their transient nature means that garments are not designed for laundering during their short lifespan, eliminating water usage alongside laundry detergents during the use phase of the lifecycle.

Soil Quality: This research has focused on improving soil quality via compostability to aid various microorganisms such as bacteria, fungi, insects, and other organisms. Although this goal was prominent throughout the practice, from initial experimentations with raw material (Ex 2 & Ex 3) to the development of lab-produced monofilaments (Ex 14) and coloured monofilaments (Ex 15), it was not until later in the research that we could begin to test the compostability of the explored casein-based materials (Ex 18 & Ex 19). The results of Thermophilic testing on casein monofilaments (Ex 19) suggested that the monofilaments in their current state were very quick to decompose and had 100% disintegrated within 45 days. This is a promising start; however, EcoTox Soil Analysis and Plant Growth Response Testing are required (on both dyed and undyed monofilaments) to understand the impact of materials on soil quality fully.

Certain decisions were made throughout the practice, such as using food waste for dyes (5.3.1), in the hope that including additional food waste sources would further improve soil quality; however, this is another area of the research that requires further exploration and testing. Regarding the envisioned supply chain for casein-based materials as outlined in Chapter 6 (p211), the composting of TCGs would either be disposed of in a domestic composting bin (aiding local organisms and soil quality) or collected and composted for use as a fertiliser to encourage the industrial growth of crops & provide feed for livestock. This model is still speculative and relies on further testing to distinguish the necessary conditions for casein-based materials to disintegrate and benefit the soil. This also depends on additional stakeholders, such as governments and councils, to set new regulatory standards for composting materials at a household level.

Waste: As a central theme throughout this thesis, reducing and recapturing waste by creating circular and regenerative systems was a top priority. Waste takes many forms and can overlap with themes of water, soil quality, and ecosystems. It can occur at any stage of the supply chain via waste materials, wastewater, chemical waste, energy waste and waste products sent to landfill. The design and development of casein-based materials and TCGs reduce waste holistically throughout the supply chain, from utilising industrial waste to eliminating waste at end of life. The removal of hazardous chemicals during hardening and the wet-spun dyeing process (using natural dyes) contribute to a more efficient manufacturing process, reducing opportunities for waste in the form of chemicals, water, and energy to be created.

The design of TCGs in this thesis focused on non-traditional garment construction methods, allowing for quick consumption and decomposition (Ex 20-26). Although some waste was created during pattern cutting, garment shapes were based on basic square or rectangular pieces which could fit together side by side on the fabric. More complex garments (looks 4 & 7) with curved seams were also envisioned to fit together on the cutting table, creating as little material waste between pattern pieces as possible. The use of tied seams (which use more fabric than a traditional seam) was justified through the lack of a cotton or polyester thread. Any scraps of material wasted through this cutting process would also be collected and composted.

Ecosystems: Creating safe and nourishing ecosystems for all human and non-human stakeholders also overlaps with each of the covered themes. Waste, water, and soil quality all impact various ecosystems through issues such as contamination (to land or water), loss of land and natural habitats, and access to food, clean air, and water. By creating non-toxic, compostable materials and garments, this research has supported ecosystems through the various points discussed:

- Improved soil quality.
- Reduced water consumption and avoidance of water pollution via toxic dyes.
- Avoiding waste sent to landfill.

Delving deeper into ecosystems, it is also necessary to explore the initial raw material stage, including dairy farming and manufacturing processes within the dairy industry. Farming practices significantly impact ecosystems (2.4), which must be thoroughly investigated on a case-by-case basis.

Although four of the themes were not directly covered through the practice-based experimentation, they each still served as a topic of investigation and contributed to the research regarding the development of speculative casein-based systems and the overarching vision:

Well-being: Well-being was addressed by eliminating toxic chemicals during material production, leading to a safer manufacturing process for factory workers and a safer material for consumers to wear against the skin. Similarly to ecosystems, the aim to create nourishing, compostable materials also acknowledges the well-being of microorganisms in the soil, aquatic life and natural habitats. From a farming perspective, the well-being of livestock is also an essential factor.

Land: The primary way that land has been considered in this project is at the beginning and end of the material/product lifecycle. At the start of the lifecycle, farming practices must ensure land is used and maintained to provide safe habitats for livestock and local wildlife and encourage biodiversity and carbon capture. At the end of the cycle, compostability is designed to reduce the use of landfills and eventually reclaim these spaces as natural, green spaces and habitats.

Energy: The formal assessment of energy usage is a crucial stage for the future development of casein monofilaments on a commercial scale. During this research, the main priority was to develop a casein-based material through green chemistry, meaning that the focus was on material composition and the elimination of harmful chemicals. However, clean and low-energy processes for manufacturing casein fibres would be essential if this research were taken out of the lab and into a pilot stage. Whilst writing this thesis, two further papers were published reflecting the in situ colouration methodology developed in section 5.4.3, documenting further testing in this area. These papers review the environmental benefits of the methodology including reduced energy usage (Papers 5 and 6, Appendix 10.6.5/10.6.6).

Regarding the design of TCGs, a reduction in energy usage was considered throughout the design, use and end-of-life of the product lifecycle. Regarding design, quick-to-produce manufacturing methods and no-sew construction methods reduce energy by cutting out the use of sewing machines. As garments are designed for single or limited use, no laundering or general product maintenance is required. At the end of life, the ability to compost garments whole without separating materials or components or undergoing an energy-intensive recycling process is also likely to reduce energy consumption drastically.

Equity: Closely tied to well-being, equality is considered regarding social and economic equity, including fair wages for workers across the supply chain, affordability, and ease of access to regenerative products for consumers of varying demographics. Although it was not possible to do a cost analysis of casein-based materials at lab-scale, this is again an important area to consider when moving into pilot scale. During the design of TCGs, cost was considered whilst exploring methods such as mono-materiality and quick to produce methods of construction, which would inevitably help to keep production costs low.

7.1.2 Designing With Casein

The practical outcomes include a range of casein-based textile samples and subsequent speculative garments. While this simplifies the overall process, it illustrates the innovation achievable through casein's integration with the RDF. Due to the lab-produced materials being under development, commercial casein materials were utilised throughout most garment development stages. This dual experience of working with both lab-produced and commercial casein materials offered valuable insights into the transition from one stage to the next and how fashion and textile designers can facilitate this progression.

Building on the concept of simultaneous design, the role of the textile designer, as defined in this thesis, takes a central place in combining the technical aspects of the RDF with the requirements for aesthetically and emotionally pleasing garments. The textile designer's work usually happens before that of the fashion designer; however, in this case, the fashion designer is also the textile designer, allowing for a holistic design process between material and garment.

The opportunity for the fashion and textile designer to be involved with material production at lab-stage is a rarity (Kapsali & Hall, 2022); however, this experience offers a greater understanding of how materials might be employed through garment design. Designing with lab-based casein materials (5.4.4) allowed for exploring novel textures, colours, and structural properties that might not yet be available in the commercial market. These experiments helped us push the boundaries of what casein can offer regarding design possibilities.

Figure 204 demonstrates the possibilities and the difficulties of designing with casein through a SWOT analysis. Internal strengths and weaknesses of designing with lab-made and commercial casein materials are presented alongside the broader external factors which could help or hinder casein as a scalable textile fibre. Some factors have been proposed as strengths and weaknesses where further development is still required. Durability is one of these elements, which must be low enough to match the garment's lifespan and quickly decompose, but also requires enough strength to be initially woven and worn, even if only a handful of times.

The juxtaposition of these two experiences offers a more comprehensive understanding of how to bridge the gap between laboratory innovation and real-world application in the fashion industry. The collaboration between scientists, engineers, and designers is essential to ensure that regenerative materials like casein can successfully replace traditional, petroleum-based options.

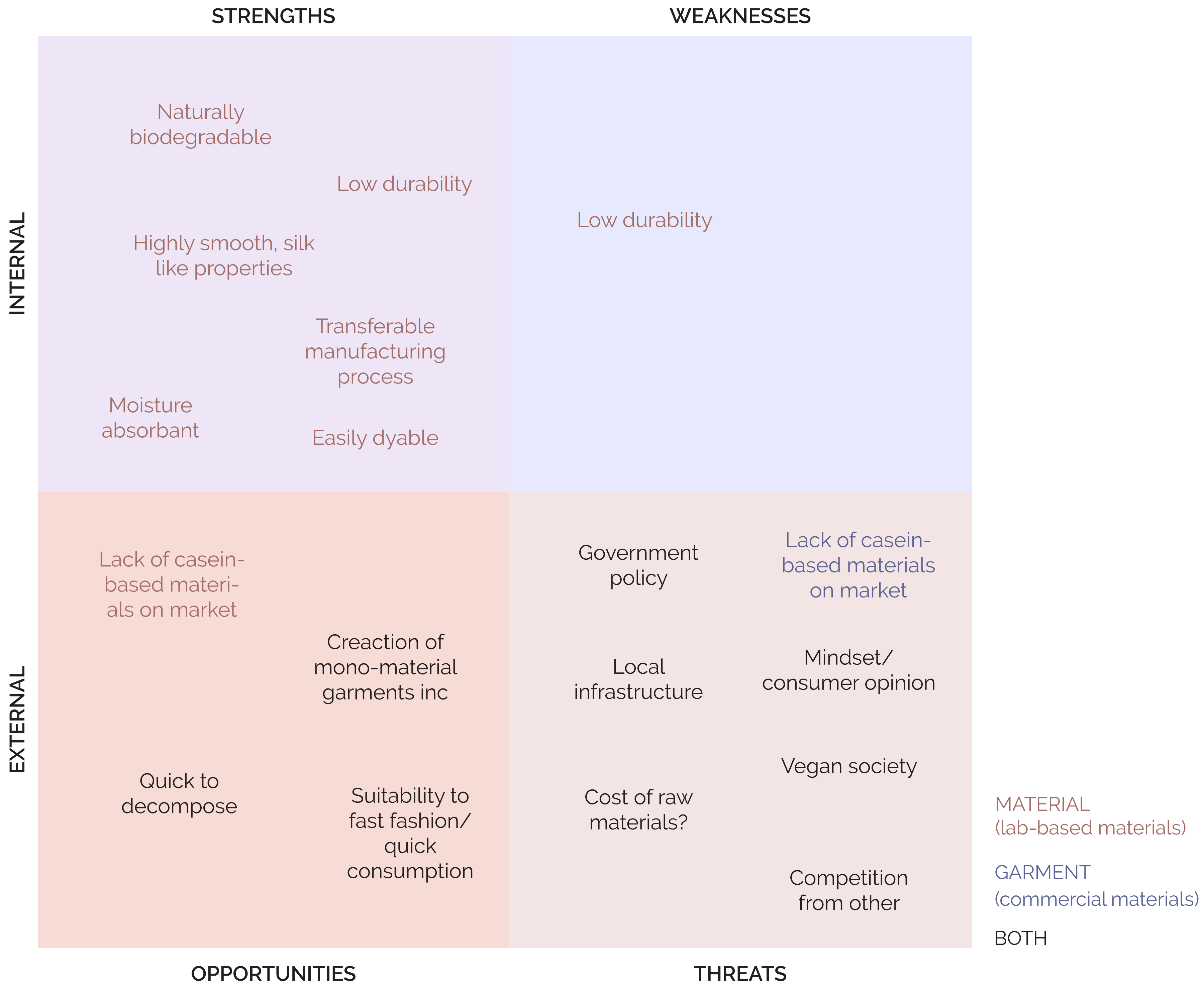


Figure 204: SWOT analysis demonstrating the internal and external strengths and weaknesses of casein as a raw material.

The following reflections cover the three main areas of designing with casein as covered in this thesis: textile design, garment design and the design of a casein-based product lifecycle.

Textile Design: Valuable insights were gained regarding material development and textile sampling by designing with commercial casein fibres and lab-produced monofilaments. Commercial yarns were explored first whilst the monofilaments were under development. Early on, it was observed that the yarns easily absorbed colour and were more colourfast than the commercial casein fabric (Ex 6), which presented difficulties in colour stability.

The commercial casein yarns were offered in various weights, allowing for a broader range of combinations regarding weave structure and the weight of final materials. Commercial samples were much heavier and softer than the monofilament samples and had a fluffier texture. The commercial yarns' fluffy nature meant some snagging occurred during weaving, particularly with tighter woven samples. Overall, however, the commercial yarns were pleasant to handle and weave.

On the other hand, weaving with lab-produced monofilaments produced a much thinner, smoother range of samples. Monofilaments dyed during wet spinning had a strong, more colourfast pigment with a crisp, clean finish. The difference in weave patterns gave each sample a drastically different handle and weight. The lab-produced materials held shape well but were still more delicate than the commercial samples.

These findings suggest that lab-produced monofilaments have potential advantages in colourfastness and achieving a clean, snag-resistant finish. However, further development is necessary to improve their durability and flexibility without using formaldehyde. Regarding the future development of woven casein materials, further improvements to durability are required so that they can be woven into the warp and weft (whilst remaining low strength compared to polyester or cotton yarn) to create a non-blended fabric. The monofilaments also require more flexibility without snapping. This area could potentially be improved by further developing the ESR drawing and drying systems.

Garment Design: Using commercial casein materials throughout the garment development stages presented its own set of challenges and opportunities. As only one woven casein fabric was available on the market, there were no other choices to explore fabric weight, texture, or handle of the fabric and incorporate these into garment designs. The available fabric was very thin and lightweight and tended to crease easily. Although this information could not be confirmed, it is also likely that the commercial fabric is still made using formaldehyde.

Although these properties created difficulties during the sampling of garment features (6.3), it was still possible to gain a sense of the visual effects and functionality of TCGs made with the commercial casein fabric. Once this sense had been achieved through sampling, the design process was continued digitally, utilising both sets of woven samples (Looks 1-8). Early design work into colour and screen-printing was also brought back in at this point. Again, using physical sampling to assess how materials responded to colour and print before taking the results into a digital space provided the knowledge to make informed design decisions.

Lifecycle: The potential for taking casein forward lies in its refinement as a material and its integration into the fashion industry. Further research into scalable and sustainable production methods for casein is crucial, as is raising awareness among stakeholders about the benefits of this regenerative material.

Casein has demonstrated significant promise as a regenerative material for use within the FTI. Its natural decomposition aligns well with garments designed for short-term use, which can then seamlessly reintegrate into the ecosystem without environmental damage or waste creation. The speculative lifecycle for casein-based garments, demonstrated in Figure 136 (p211), was developed in response to the need for local and regenerative systems from food waste. Retrospectively, this lifecycle also serves as a roadmap to identifying further areas of R&D for designing with casein, from lab-based experimentation to commercial application and end-of-life.

In a broader context concerning RPFs, the selection of casein as the material of focus was influenced by its widespread availability in the UK as a source of industrial waste. Nevertheless, it is acknowledged that consumer preferences may shift towards a vegan lifestyle in the future, potentially altering these circumstances and reducing the reliability of dairy farming.

A crucial facet of this research is its adaptability to local waste streams and infrastructure. Therefore, a necessary area for further development is the lab-scale testing of the developed processes on other forms of protein derived from alternative sources of food waste (such as peanuts or corn). Creating a transferable framework for other RPFs would help support local needs alongside a broader transformative shift towards regenerative textile manufacturing systems.

7.1.3 Designing for Transience

The decision to design for a transient fashion market stemmed from various points within the research. These points were continuously connected throughout the historical and contemporary investigations between researchers. The literature review uncovered that casein was disregarded as a textile fibre due to poor tensile strength and durability, stating that many of the patents filed between 1896 and 1963 were an attempt to fix this issue (p29). From a technical standpoint, the topic of strength and durability is closely connected to the use of formaldehyde during the hardening stage of fibre production (2.2.2). This connection sparked debate between researchers surrounding the concept of quality and durability regarding the 'necessary' lifespan of garments and the assumed requirement to create more robust materials.

During the practice-based research, the requirement of durability was reflected upon repeatedly. Working with casein first-hand led to a new understanding of its natural properties (5.2). During this time, the RDF was under development and responsible disposal of materials at the end of their useful lifespan became the priority. At this point in the research, the low durability of casein became an opportunity to create a material with a different value. From a contemporary viewpoint, the literature review and consumer survey also uncovered a disconnection between material, garment, and longevity (2.3.2, 4.1.2), highlighting that the circulation of new trends generally takes priority over quality.

Since this survey was conducted, WRAP (2022) conducted two large-scale pieces of online consumer research estimating clothing longevity for specific garments. The key findings from this study show that garments have an average longevity of 4.3 years, with 87% of consumers still choosing to purchase new clothing over vintage clothing or using rental services. It also showed that 22% of respondents consciously avoided last season's clothing, with a demographic overlap (23%) observed with those who only buy clothing for short-term use.

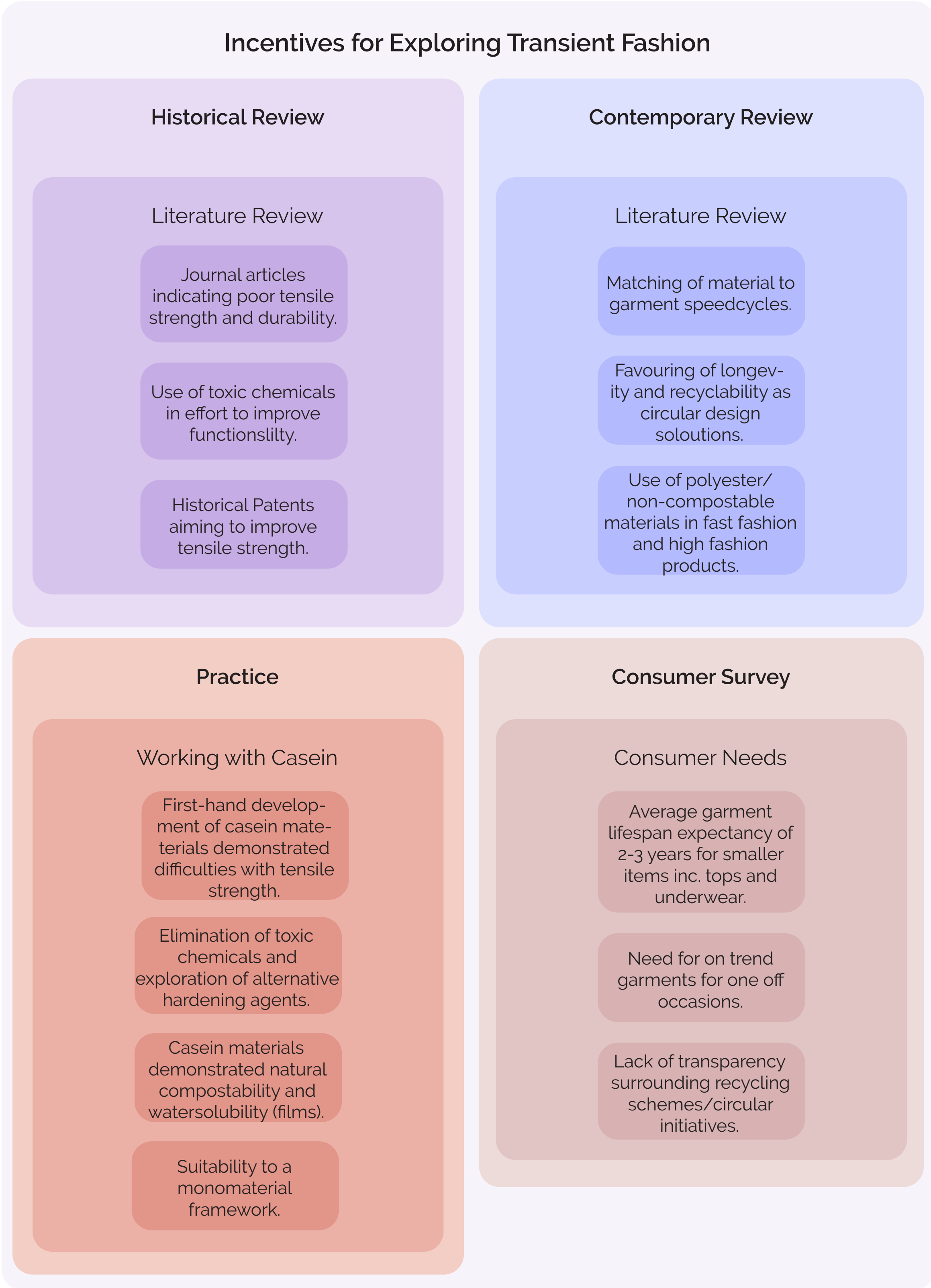


Figure 205: Incentives for exploring transient fashion.

In this report, clothing longevity is calculated as the amount of time since respondents acquired the item of clothing plus the anticipated amount of time they expect to wear it (Table 31). These figures have been recorded and compared to the consumer survey findings (Chapter 4) to identify any crossovers or conflicts in results and add a new lens for future research in this area.

Item of clothing	WRAP (Number of years owned + future life expectancy)	Consumer Survey (Expected lifespan, years)
Non-padded coat	6.3	10+ years
Non padded jacket	6.1	
Padded jacket or coat	5.4	
Skirt	4.9	
Knitwear	4.8	
Shorts or cropped trousers	4.8	
Protective overalls	4.8	
Dress	4.6	4-5 years
Pyjamas/nightwear	4.4	
Sweatshirt/hoodie	4.4	
Trousers (chinos or suit)	4.3	
Jumpsuit or playsuit	4.2	
Work uniform	4.1	
Shirt/blouse	4.1	2-3 years
Jeans	4.1	2-3 years
T-shirt/polo shirt	4.0	2-3 years
Leggings/exercise bottoms	3.8	
Socks/hosiery	2.9	2-3 years
Underwear	2.7	
Bra	2.6	
All	**4.3**	**2-3**

Table 31: Mapping garment longevity

Although the WRAP report features a more extensive list of garments than the consumer survey, it also demonstrates a mixed consistency between responses. Generally, the average longevity of items was higher for the Wrap report (4.3 years) than the survey (2-3 years), demonstrating higher longevity for items such as shirts, jeans and underwear, lower longevity for jackets/coats and equal longevity for dresses. These findings underscore the multifaceted nature of clothing consumption and its relationship with longevity, personal expression, and seasonal preferences.

As with much of the research in this area (Ellen MacArthur Foundation, 2017; House of Commons, 2019; WRAP, 2014), this report is part of a movement towards improving the longevity of clothing and textile materials - mainly through recycling - a key focus for the Textiles 2030 Circularity Pathway (WRAP, 2021). What such reports and initiatives fail to address, however, is that textile recycling cannot be the one and only solution and that the opportunity to design garments for a transient market could not be more relevent.

Using information from WRAP and the consumer survey, Figure 206 maps out the spectrum of longevity considering the average life expectancy of garments. Thompsons Rubbish Theory is applied to the X axis, placing rubbish at the very beginning of the spectrum to represent raw material in the form of either food or agricultural waste or recycled textile fibres. Transient is in the centre of the spectrum, representing all forms of garments during consumer use. Durable is placed at the end of the spectrum, representing high-value vintage garments, couture, or archive collections.

The Y axis reflects material strength and overall garment quality. Singe use items, including one-off party wear and hygiene products such as PPE, are at the top left-hand corner, demonstrating the balance between longevity, material strength and construction. Jackets and coats were nominated as having the highest life expectancy and are placed in the bottom right-hand corner, balancing their lifespan with higher-quality materials and construction.

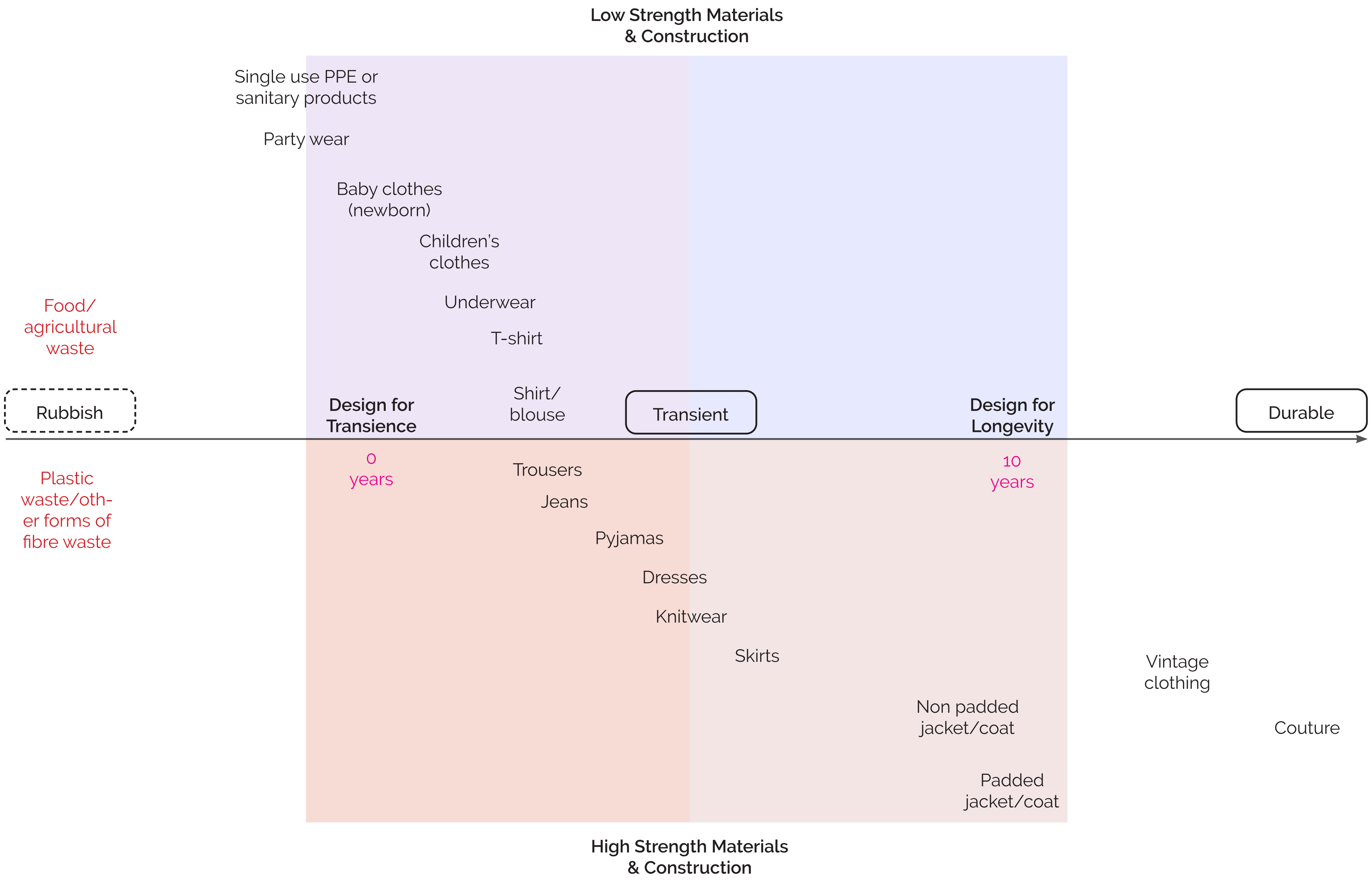


Figure 206: Mapping garment longevity against material strength and construction based on consumer survey and Wrap survey results (WRAP, 2022).

Overall, this image demonstrates the narrow parameters in which we (as a society) view longevity. If ten years is the longest time we expect any item to last (or choose to wear/ keep a garment), why are we looking for ways to extend the useful lifespan of garments further? Surely, when considering the complexities of consumer expectations, the prolific issue of waste and the current consensus of circular design to reflect longevity, there must also be an alternative solution catering to transient lifecycles.

Although Figure 206 maps garment lifespan and material durability as a linear spectrum, there is flexibility for garments to move around this map depending on circumstances. For example, children's clothing has been placed in the top left corner as children quickly grow out of their clothing. As with party wear or garments for one-off use, this presents an opportunity to create clothing for quick consumption; however, this could be achieved through composting or resale, reflecting two different material cycles.

Methods of Design: Rather than creating timeless pieces that would endure for seasons or even years, designing for transience involves a shift towards creating intentionally temporary garments designed with a shorter lifespan in mind. This approach necessitates designers to consider factors such as compostability and material value from the beginning of the design process. It also requires designers to work with textile developers to understand their material choices beyond fabric composition, including textile processing and colouration techniques.

Designers should know precisely what chemicals have been used to manufacture a material, as well as the associated water and energy usage. Without this knowledge, how can designers best understand the implications of the products they are designing or how can they appropriately advise consumers regarding garment care and disposal?

Within this research, garments were considered alongside the textile development process. As a designer, this gave me a new outlook on what properties and features were suitable, simultaneously from both a material and garment perspective. Although the design of TCGs is somewhat speculative, developing this design process was necessary to understand the potential of materials being produced in the lab. Regarding matching of speedcycles, material and garment must work harmoniously to generate as little impact throughout the supply chain as possible.

Mono-Material Production Methods: Mono-material production methods are a vital component of designing for transience. Blending of fibres is generally done to enhance material properties and functionality, such as strength, durability, and elasticity. However, such properties are less critical when designing products for a short lifespan. Compostability at the end of life becomes more feasible by using a single material type throughout a garment›s construction, eliminating time and energy spent separating materials or components.

During the design of TCGs, the aspect of mono-materiality was kept at its simplest and did not go on to include components made of galalith (Ex 1). This was mainly down to the decision to use no-sew construction methods, stripping garments down to their most basic form and prioritising quick manufacturing process and ease of degradation. This element of simplicity became one of the most significant challenges in the design of TCGs. However, stripping a garment back to its basics and unlearning traditional design methods encouraged more of a free-thinking approach towards construction.

No-Sew Methods of Construction: Traditional sewing techniques often result in garments with multiple components and seams, making disassembly for composting or recycling challenging. No-sew methods of construction offer a solution to this problem. Techniques like heat bonding (Jevšnik, Vasiliadis et al., 2016), laser finishing (Goldsworthy, 2012), and 3D printing (Wightman-Stone, 2023) enable the creation of seamless garments, reducing the complexity of disassembly and increasing material recovery rates. Such methods open multiple avenues for new design and aesthetic appeal, such as clean and minimalistic designs or added decorative features.

In the case of TCGs, no-sew construction methods significantly contributed to design attributes by tying together seams. Unlike previously mentioned methods, this method was designed to be low-tech and low-resource but still have a visual impact. Rather than using darts or traditional tailoring to create shape, the ties become the central point of structure determined through the warping and ruching of seams.

Consumer and Industry Preconceptions: The design of TCGs has benefits such as reduced material waste, increased compostability, and alignment with changing consumer preferences. However, TCGs may still face challenges related to durability and the desire for more frequent purchases, conflicting with traditional sustainability goals supporting garment longevity.

Balancing these factors within the regenerative fashion economy is essential for its success.

Creating new, regenerative systems also opens the door to new economies of scale and retail options, all of which should be considered holistically. In this way, there is scope within the design of TCGs to meet numerous consumer requirements regarding the cost and frequency of new styles without the need to mass produce. As the focus for TCGs is on creating exclusive outfits for one-off occasions or short-term wear, it stands to reason that small batch production of garments would enhance exclusivity whilst reducing the risk of overproduction.

Figure 207: Lab-produced woven test strips and reels of monofilament.

7.1.4 Responding To The Vision

The vision, as outlined in Chapter 4 (p105), played a pivotal role in shaping this thesis. Working with a forward-looking and speculative vision allowed the research to incorporate various elements, including materials, waste sources, manufacturing processes, and stakeholder interests, all while keeping the ultimate objective in focus. These envisioned scenarios represented potential futures, recognising the inherently speculative nature of textile and garment design processes. The research aimed to avoid purely imaginative scenarios, acknowledging the possible existence of specific industrial processes for new materials in short-life garments and adopting particular behavioural habits for long-life garments, even if they do not currently exist but hold promise for the future. The primary objective was not to report on established practical solutions but to explore the environmental potential of these forward-thinking ideas.

Within the context of the garment design process discussed in Chapter 6, the vision underwent reinterpretation and refinement in the form of a design brief (5.2.2). A design brief is described by Sinclair (2014) as a method of 'research for design' and offers commercial fashion design direction. In this research, the design brief provided a more detailed roadmap for how specific aspects of the vision could be expressed through the design of TCGs and how design fits into the broader context, bridging the ecological ceiling and the social foundation.

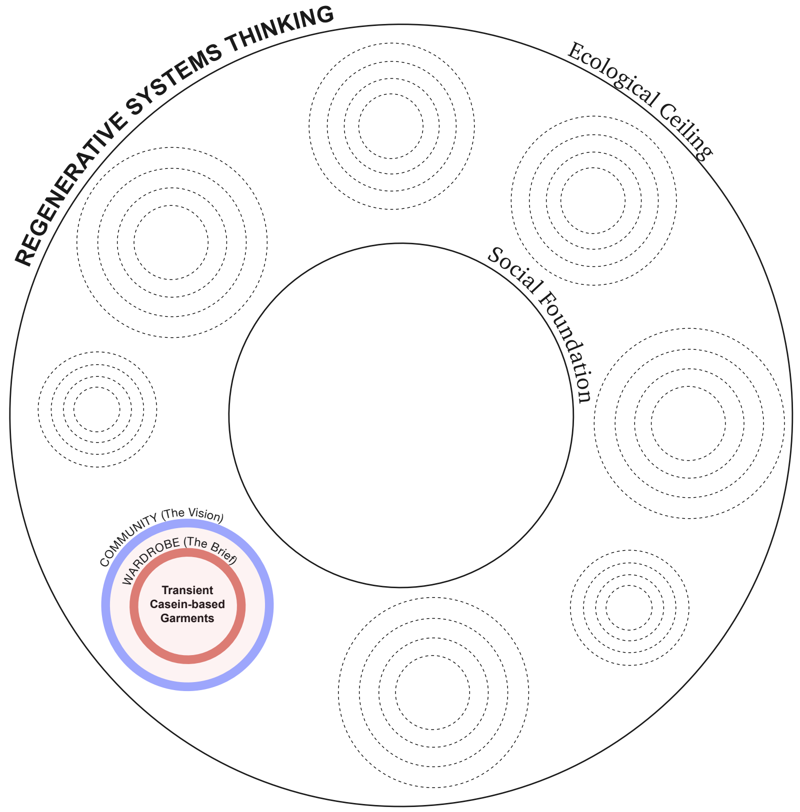


Figure 208: How the brief sits into the broader vision and worldview.

Once again, operating within this forward-looking framework that balances emerging technologies, societal expectations, and local infrastructure facilitated a more speculative design response. Congdon (2022) discussed that a critical advantage of speculative design lies in enabling designers to engage with technologies they may not yet be able to access. Given that the ESR was still under development for most of the design work, much of the design efforts had to rely on commercial materials as the primary reference point while contemplating the potential contributions of lab-produced materials.

Malpass (2013) warns that the notion of speculative design (and potentially the presence of an overarching vision) in guiding the research could lead to excessive self-reflection. However, as Ackoff (2006) argued, designers can forge novel pathways through reflection, logical reasoning, and the generation of creative, speculative ideas. To achieve this, the creative outcomes of the design process are best realised within collaborative communities of practice (Goldsworthy & Earley, 2017: p. 394).

Throughout the research, the speculative nature of the vision closely aligned with the transdisciplinary practice. This synergy helped to keep areas of practice grounded, such as what was achievable in a laboratory setting, while fostering a more imaginative approach in other areas, such as the design of TCGs. Although it could be argued that a research team is still a closed community, working across disciplines and having the opportunity to exchange ideas and concepts relating to the vision prevented the research from becoming one-dimensional at any given juncture. This blend of speculative thinking and real-world practice enabled the team to anticipate design outcomes rather than merely reacting to circumstances, placing physical materials (and speculative garments) within the framework of material and immaterial systems.

In addition to steering the research, the vision also conveys ideas to an external audience. As discussed by Dunne and Raby, speculative design aims to "create spaces for discussion and debate about alternative ways of being, and to inspire and encourage people's imaginations to flow freely" (2013: p. 2). In line with Dunne and Raby's vision (2013) of design as a tool to create ideas and 'things', speculation has been instrumental in informing how 'things could be' in this potential future. By proposing a level of systemic change, the research sought to understand the necessary technological and societal shifts explored through the design brief. In this manner, the concept of TCGs and design for transience was conceived as a catalyst for stimulating discussion and reflection on prevailing consumption habits and manufacturing systems, with pragmatic feasibility being a secondary concern at this stage.

In terms of translating the vision and how it has been developed and portrayed throughout the research, Figure 209 builds upon Figures 35 (4.3) and 206 (7.1.3) to map out the spectrum of longevity from transient to durable within various material systems. When the vision was first outlined in Chapter 3, areas of the supply chain and key stakeholders were identified within a local, regenerative system focusing on food waste as a raw material. Figure 209 reimagines this system within the broader context and demonstrates the scope of opportunity for transient, compostable garments alongside the various forms of material value and the transfer of material value. This image again highlights the importance of transient materials within a system where virgin materials are no longer created, and instead, everything is reused or repurposed.

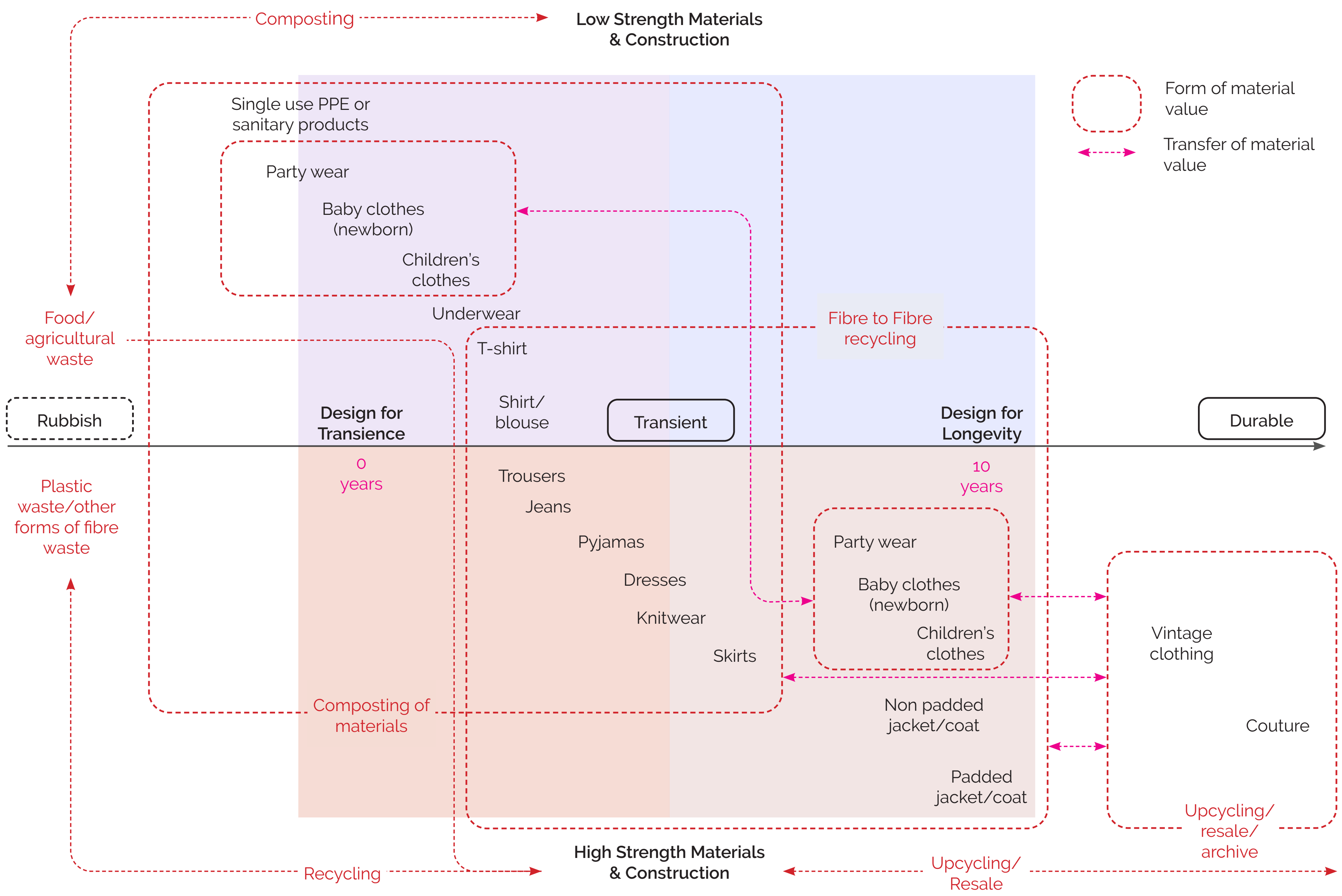


Figure 35 (revisited, p106): Demonstrating the future vision of a regenerative local economy for transient, casein-based garments.

Figure 209: Materials derived from food or agricultural waste span RPFs and various forms of biomaterials, including pineapple leather, mycelium-based materials, and bacterial cellulose, each of which represents a range of diverse material properties and qualities and could fall into either compostable, biodegradable or recyclable. As with recycled polyesters or petroleum-derived materials, recyclable biomaterials would demonstrate superior durability and strength to RPFs or materials designed to be compostable.

The following stages of this research would involve engaging with a broader spectrum of stakeholders to evaluate the research outcomes in response to the vision. This includes further surveys and conversations with consumers to refine our understanding of their evolving needs and desires. Industry stakeholders, including manufacturers, retailers, and policymakers, should also be included in this ongoing dialogue.

7.2 Methodological Framework

In this section, the critical role of each research stage (Explore, Experiment, Evaluate) is analysed in conjunction with the ten methods employed. The practice-based outcomes and innovative theoretical concepts developed between participating researchers are discussed within the parameters of the transdisciplinary research process. The relationship between collaborators and the integration of design expertise with scientific knowledge is also reflected upon.

7.2.1 Transdisciplinary Relationships

Since the beginning of this project in 2019, transdisciplinary research has gained increasing momentum within both the design and scientific communities (Hahn, Kirschke et al., 2023; Hepburn, 2022; Lawrence, Williams et al., 2022; Mejia, Henriksen et al., 2023). This burgeoning interest has made keeping pace with the influx of new and pertinent information challenging. The shift from interdisciplinarity to transdisciplinarity, now a prominent buzzword, signifies an evolution in the comprehension and practice of collaborative approaches. Furthermore, the widespread referencing of transdisciplinarity in the literature reflects its increasing influence and acceptance as a successful approach for addressing intricate challenges.

As illustrated throughout this thesis, transdisciplinarity underscores a holistic and integrated perspective that transcends disciplinary boundaries, nurturing profound connections and knowledge exchange across diverse domains. Nevertheless, it is not without its challenges. A crucial point underscored by Lawrence, Williams et al. (2022) is the imperative to eschew oversimplification, recognising that transdisciplinary research is more than just "talking tables"; it necessitates deep engagement. Involving non-academic stakeholders (including designers) in transdisciplinary research goes beyond surface-level participation. It entails empowering these non-academic actors with decision-making authority to assume pivotal roles in fostering heightened levels of engagement.

As suggested by Delamont, Atkinson et al. (2000), it has become evident in this research that, despite differing disciplinary backgrounds among researchers, a genuine eagerness to learn and embrace each other's areas of expertise has significantly contributed to the project's success and outcomes. The shared enthusiasm for the research topic has fostered an open and transparent dialogue among researchers, facilitating the organic evolution of innovative ideas throughout the project.

A critical factor in achieving success is a sincere commitment to cross-disciplinary communication without emphasising immediate results. This attitude demonstrates a willingness to invest time in identifying connections and initial opportunities (Brodin & Avery, 2020). Although there was initial pressure for JH to produce technical results in the early stages of the project, the

initial phases of laboratory-based material development involved exploring existing production methods identified during the joint literature review conducted at the outset of the transdisciplinary journey. This early opportunity to delve into a common theme of historical production processes, both individually and collaboratively, allowed for resource sharing, knowledge exchange, and the shaping of outcomes, establishing a dialogue and identifying common areas of interest through the literature review.

In addition to ideation and knowledge exchange, biweekly check-ins with JH and HAG provided personal support. Maintaining an open working relationship and the opportunity to discuss matters related to the PhD and the broader work package (WP6) brought an essential additional level of interaction to the project. In turn, this helped me as a researcher to feel more comfortable in my working space (both mentally and physically), particularly during periods of lockdown, which otherwise could have been isolating.

As detailed in Chapter 3 (3.1.2), practice-based design research and design in academia, for that matter, constitute a relatively new field (Ellams, 2016). Establishing transdisciplinary relationships from both an academic and social perspective has proven invaluable. Participation in such a supportive network among project partners and collaborators helped researchers stay on course and navigate the research journey. This support enhanced confidence and ambition regarding what could be accomplished within the PhD's timeframe.

Initially, the hypothesis was that a 'successful' outcome necessitated a comprehensive understanding of both disciplines by JH and me. However, as we collaborated on the literature review for our first co-authored publication (Stenton, Kapsali et al. 2021), we encountered barriers between design and scientific languages that could be frustrating. This perspective shifted as we engaged in more frequent and in-depth conversations, enabling us to question specific terminology and gain insights into the work conducted at UoL. Learning through a combination of written reports and conversations also helped clarify particular roles within the project and what was expected from each researcher's contributions.

The resulting integrated relationship among researchers complicated tracing the origins of specific inputs and ideas. The perceived role of the textile designer as a 'middleman' often puts the contributions of designers at risk of being overshadowed by other disciplines (3.1.2). In this project, however, mitigation was achieved by acknowledging that each researcher produced unique outcomes, with no contribution going unnoticed. Trust played a pivotal role in this context. Allowing each researcher to generate independent results and subsequently coming together to build upon those results collaboratively provided a harmonious structure while fostering individual growth and independence as researchers. The co-authorship of research papers also contributed to participant engagement and facilitated the sharing of recognition.

Six peer-reviewed papers were published throughout this project, serving as a roadmap and timeline for developing theories and achievements alongside key contributors.

Figure 210 demonstrates the development of new knowledge between researchers and the nurturing of our own individual outcomes. We each contributed to the overall project (WP6) in our own ways, utilising our tacit knowledge and expertise to solve problems and create unique project outcomes in response to the brief.

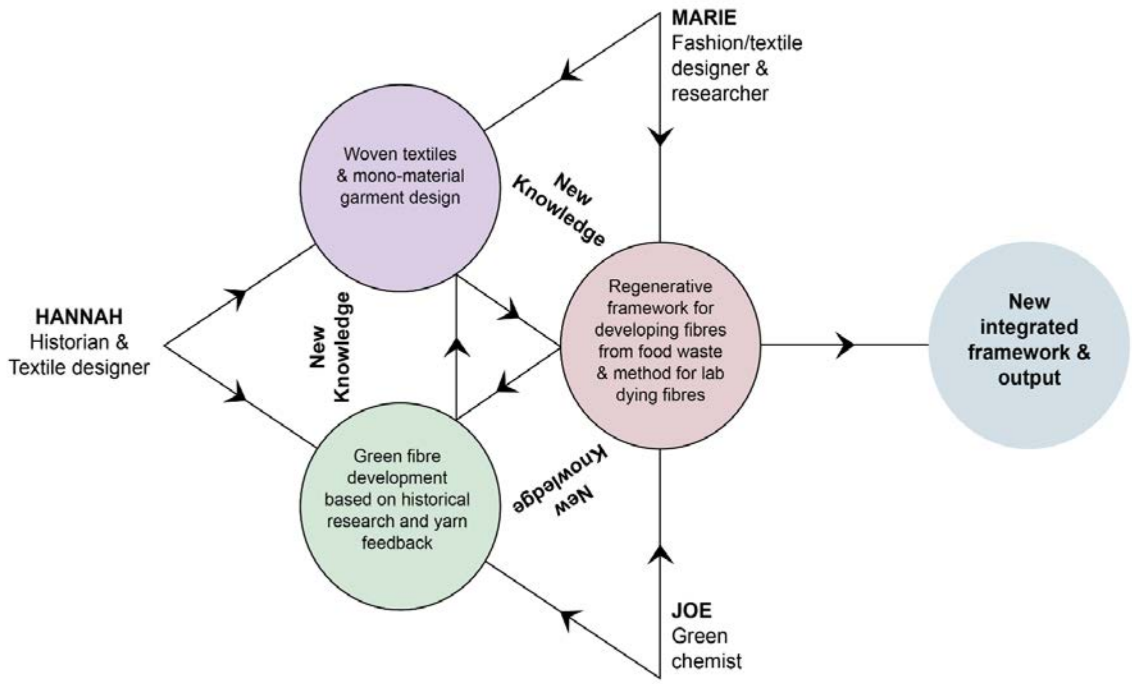


Figure 210: The development of new knowledge between researchers.

7.2.2 Transdisciplinary Outcomes

Lawrence, Williams et al. (2022) discuss the challenges in evaluating transdisciplinary research projects, distinguishing between two categories of evaluation: assessing project effectiveness in terms of processes and outcomes and assessing broader impacts, such as contributions to sustainability transitions. While measuring project processes and outcomes is relatively straightforward, evaluating broader impacts is more challenging but often crucial for non-academic participants (Lawrence, Williams et al., 2022). In addressing the difficulties of evaluating transdisciplinary research projects, assessing how these challenges have been tackled is essential. This includes systematic assessments of how academic and non-academic actors have been integrated throughout the project phases, addressing issues of power and decision-making. It also involves evaluating the integration of different forms of knowledge and the implementation of reflection and continuous learning (Mauser, Klepper et al., 2013).

Combining science, design, and archival data provided a practical approach to problem-solving. Science and history offer evidence-based insights and validate design decisions, while design humanises scientific knowledge, making it more accessible. This transdisciplinary approach enables a comprehensive understanding and innovative solutions that may not be achievable through design or science alone. For example, the use of historical data provided an understanding of the early challenges (technical, environmental, and societal) associated with RPFs and allowed for the testing of potential solutions through material sampling. Analysing historical data (such as manufacturing processes) through a contemporary lens in this way is a primary example of academic and industrial research integration through knowledge exchange between participating researchers (MS, HAG and JH).

The transdisciplinary approach in this project not only widened the scope of knowledge but also made it more accessible and applicable to a broader audience. By actively engaging in different modes of dissemination, we ensured the work had a far-reaching impact, influencing our respective fields and inspiring collaboration and innovative thinking across disciplines. Each researcher associated with the project had the opportunity to disseminate or present areas of the research through various outward-facing activities such as publications, presentations or showcases. For example, JH, HAG and I spoke at multiple conferences both collaboratively and independently, allowing us to translate varying areas of the research to different audiences. Collaborative presentations helped showcase the synergy between design, science, and history, highlighting how these disciplines complemented each other to solve complex problems. In contrast, independent presentations allowed us to delve into our specific areas of expertise, providing a deeper understanding of the nuanced aspects of the research.

Upon reflection on this section of the research, JH and I discussed the impact that knowledge exchange had on each other's work. JH felt that he learned to view chemical processes through a designer's eyes, considering the user's needs rather than focusing on the chemical results. Alongside this, he developed a new approach to problem-solving in the lab, which considers the difference between the world of the designer and the micro world of the chemist. He also recognised that although both approaches have validity, certain areas of knowledge exchange between designer and chemist were less valuable than others and had little impact throughout the development of the ESR and filament development.

The roles of the scientist (JH), the designer (MS) and the historian/weaver (HAG) are respected for their individual skills, which have become increasingly intertwined throughout the project. The relationship between researchers took an honest and open journey throughout this study to ensure equal merit and acknowledgement for contributions. Table 32 highlights each of the outcomes from WP6, considering academic, physical, and theoretical outcomes. Conferences and material showcases have been classed as forms of dissemination.

Phase	Co-creation of new knowledge	Outcome	Dissemination
Explore *(Problem Identification)*	Co-Design	ESR. **Research paper 1. 2021** Research paper 2. 2021. **Research paper 3. 2022.**	
Experiment *(Knowledge Integration)*	Co-Production	Research paper 4. 2023. **Commercially woven final samples.**	**Waste-me-not, online, 2021** Sustainable fashion: transdisciplinary approaches to innovation. Royal Society of Art 2021. **Transdisciplinary Research Can Enable The Innovative Design Of Textiles Within A Circular Economy To Produce Regenerated Protein Fibres From Food Waste. Conference: Early Careers Research Symposium. V&A Museum, 2022.**
Evaluate *(Action)*	Co-Dissemination	Lab-produced filaments & woven samples. **In-situ colouration methodology.** Research paper 5. 2023. **Research paper 6. 2024.** TCGs. **Local, regenerative supply chain from food waste.** Regenerative Design Framework. **Transdisciplinary Methodology.**	26th Annual green chemistry conference, Textile Institute World Conference. 2022. **Future Fabrics showcase @ The Sustainable Angle. 2023.** Harnessing Historical Technologies In The Development Of A Circular Textile Model: The Future Of Regenerated Protein Fibres. Conference: Textile Institute World Conference. University Of Huddersfield. 2023.

Academic Outcomes
Physical Outcomes
Theoretical Outcomes

Table 32: Research phases mapped against project outcomes and dissemination.

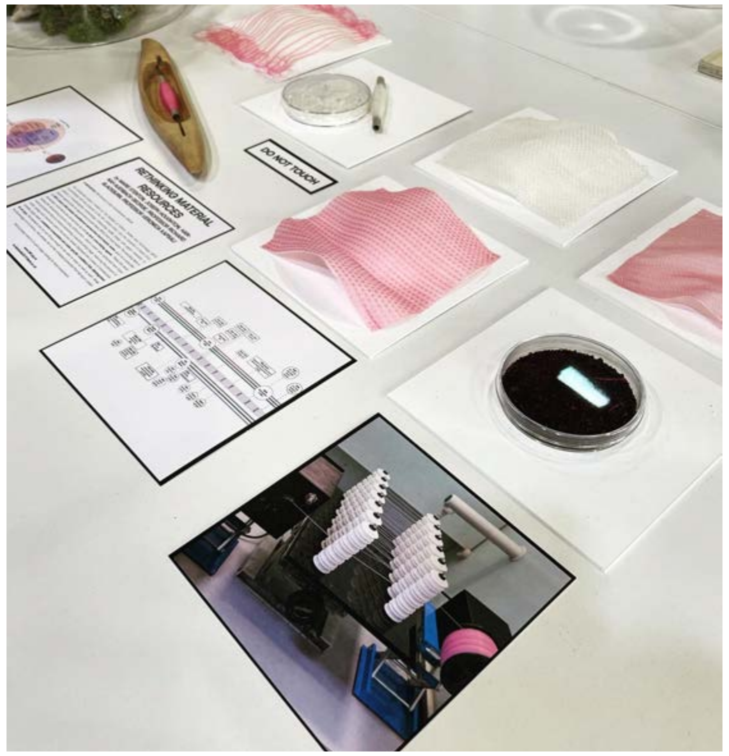


Figure 211: Display at the Future Fabrics Expo, 25th-26th June 2023.

7.2.3 Integrated Framework (Explore, Experiment, Evaluate)

As discussed in Chapter 3, ten methods have been used across three stages of this research: Explore, Experiment and Evaluate. These stages reflect a range of industry and academic approaches spanning design, science, and archive research. As the collaborative, multi-disciplinary PhD is becoming the norm, it is common practice to visually map the data and outcomes generated throughout the research to understand the complex relationships between the research model and the original contributions to knowledge.

McQuillan (2020), Forst (2020) and Hall (2021) use mapping exercises to disseminate their PhD research, connecting the research process to the insights generated. Each of these PhD theses is concerned with forms of textile-based circular design and waste reduction, and as with this thesis, employ a non-linear, multistage research methodology consisting of stages such as 'think, explore, test, reflect' (Hall, 2021) or 'scope, make, map and reflect' (Forst, 2020). While simplifying the overall processes, this methodology allows the researcher to break down and categorise research areas into more manageable stages and translate the work done more effectively to an external audience. Although the terminology is different, they each encourage a similar flow of thinking, allowing time to understand the research problem before making or experimenting and finally moving towards reflecting and evaluating the work done.

This format is particularly suited to integrated research where academic and industrial methods combine with multiple forms of thinking or wearing various hats (Hall & Earley, 2019). This multi-perspective (between academia and industry and various disciplines) is vital as they often support each other (Fallman, 2008: p. 10) and provide a better understanding of the multiple drivers, interdependencies, and complexities of global sustainability challenges. The knowledge created through integrated research can better contribute to developing robust policy solutions and their practical, equitable implementation (Mauser, Klepper et al., 2013).

The research model employed in this thesis stemmed from a combination of transdisciplinary research (Lang, Wiek et al., 2012), transition design (Irwin, 2015) and regenerative design (Reed, 2007) models. Aspects from each of these models were integrated to inform the overarching research methodology, which is reflected in the three stages of Explore, Experiment and Evaluate. Throughout the thesis, this methodology has generally been referred to as the RDF and has focused on regenerative design methods and design for transience, as discussed in practice throughout Chapters 5 and 6. However, the transitionary and transdisciplinary nature of the research has run through every stage of the project, guiding and informing the process consistently whilst informing the bigger picture.

While the research has been mapped at various points throughout the thesis, visualising and representing the holistic nature of the encompassing methodology has been challenging due to its complexity and reiteration. This methodology involves collaborating with different partners, disciplines, models, and methods. It is crucial to clarify that the transdisciplinary methodology and RDF, although separate contributions to knowledge, have a symbiotic relationship. They intertwine and inform each other, leading to the creation of a unique design-research model.

As discussed by Hall (2021) and Lerpiniere (2020) (p77), textile designers must bring together "disparate approaches, competencies and skills" to tackle the changes required in the industry, considering the entire lifecycle of a product (Lerpiniere, 2020: p. 93) engaging with both the micro (fibre level) and the macro (supply chains). As well as the technical (material) cycle, the micro and macro levels can also represent societal viewpoints regarding the wider worldview (Macro) and the localised system (Micro), both of which have been thoroughly investigated in this thesis.

Figure 212 introduces the model for Transdisciplinary Regenerative Design Research (TRDR) as used within this PhD. It demonstrates how this integrated framework and the methods used have responded to the three key factors within the research question. These factors foster transdisciplinary collaboration, promote the utilisation of casein-based materials in a regenerative fashion, and challenge prevailing notions of disposability as an indicator of quality.

The transdisciplinary collaboration between disciplines is mapped, considering the various topics explored to answer the research question. The knowledge acquired throughout this stage is continuously put into action throughout each integrated stage, flowing through the vision and the design brief and into the final outcome. Each nested methodology sits within the macro-lens of the wider worldview (planet), moving inwards towards the micro-lens of the localised vision and garment design brief. This transition inward is also representative of the design of materials whilst

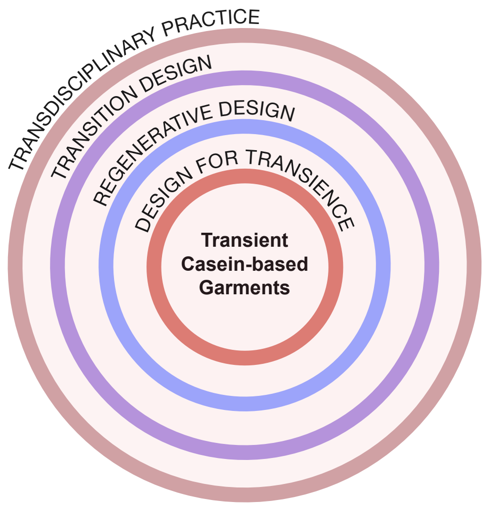


Figure 33 (revisited, p77): A nested approach to the design of TCGs.

considering the wider supply chain. As the research process circulates between these methods and micro/macro ways of thinking, it provides multiple opportunities to identify new areas for intervention and knowledge integration.

In responding to the research question and tying together each of the key areas of the research, Figure 212 also demonstrates how the two overarching contributions to knowledge (the RDF and the TRF) have come together to create a new model for TRDR. The implications of this model for future research are discussed in Section 7.3.

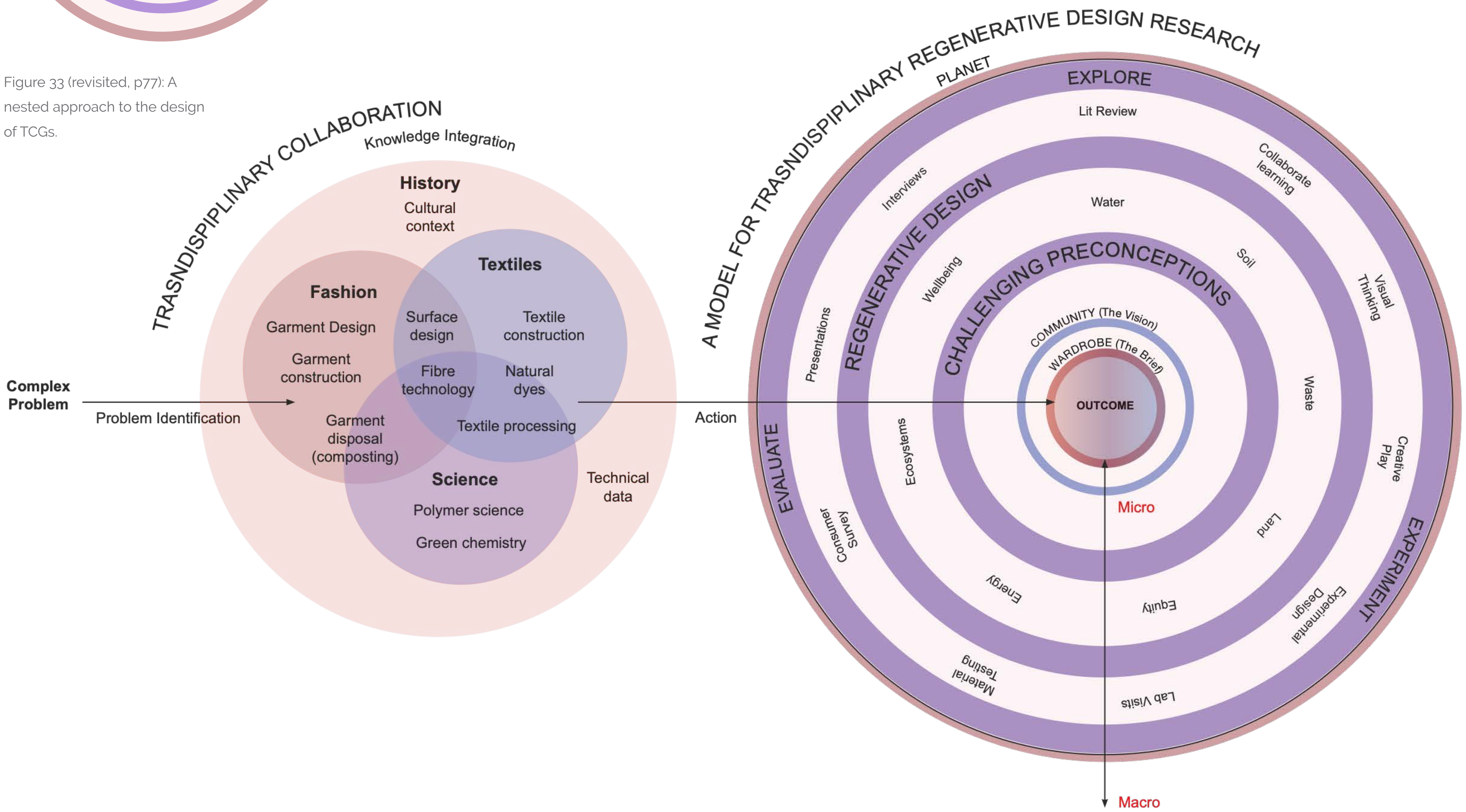


Figure 212: A model for transdisciplinary regenerative design research

7.3 Responding To Gaps In Knowledge

Alongside answering the research question, this thesis has responded to four pivotal gaps in knowledge which were uncovered during the literature review (2.5). These sub-questions are revisited and assessed in terms of how effectively they have been addressed and how they have contributed to the creation of new knowledge. These questions are:

1. Is casein a suitable raw material to produce regenerative garments?
2. What will these new, regenerative systems look like, and how will value be recaptured at end of life?
3. What policies and instruments are crucial to implementing these systems?
4. How do we ensure that the solutions put in place are in the genuine interest of all stakeholders? (Supporting people, planet, and profit).

The flow of new knowledge can be traced throughout each of the workflow models demonstrated at the end of Chapters 4-6. Figures 36, 134 and 192 follow the primary research process outlining the progression of the thesis and the subsequent physical or theoretical outcomes (exclusive of joint research papers and presentations). Figure 213 illustrates the complete workflow model, emphasising how outcomes along the way have contributed to new processes and each original contribution to knowledge.

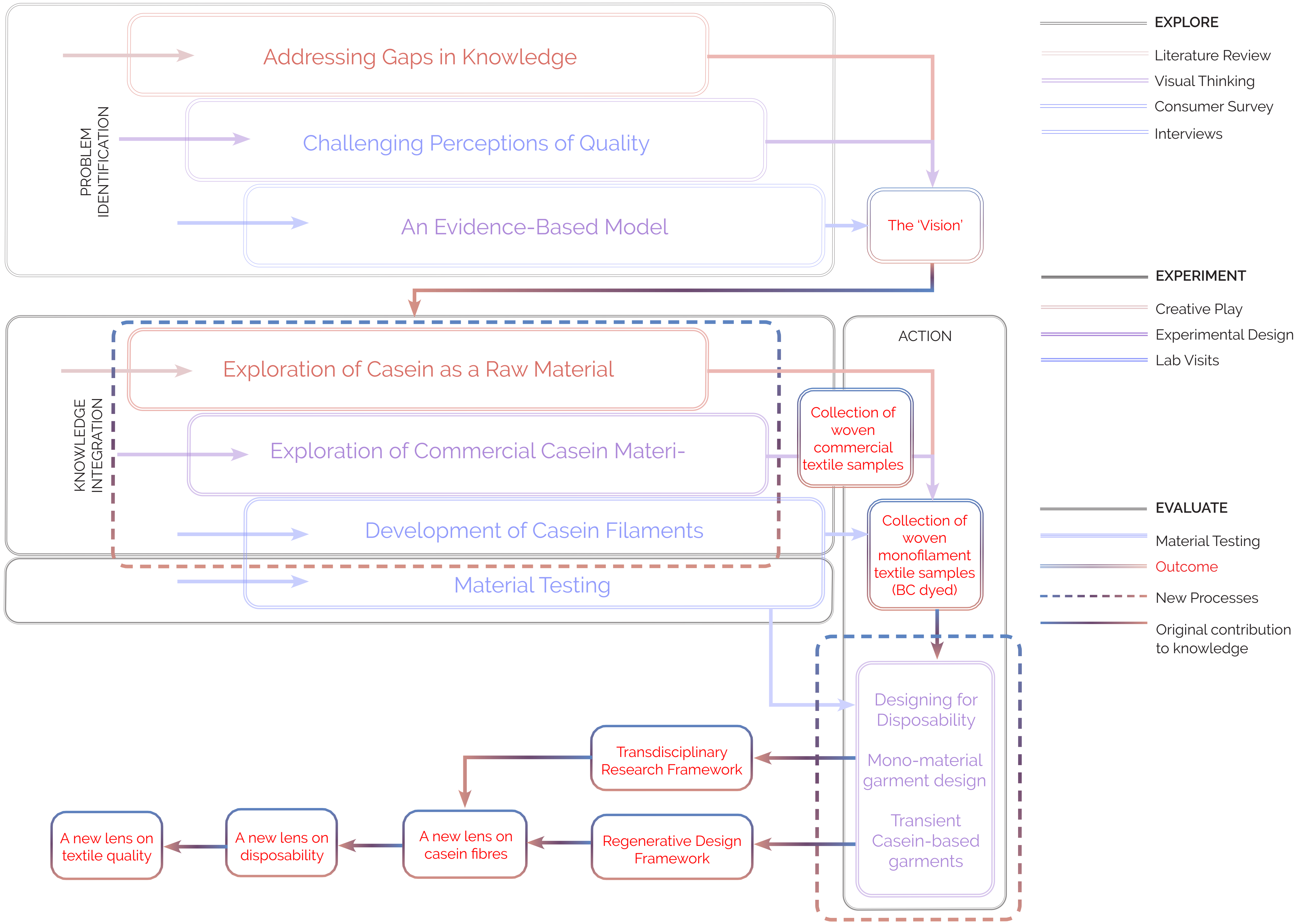


Figure 213: Complete workflow model accounting for Explore, Experiment and Evaluate.

Chapter four was pivotal in bridging knowledge gaps, with the consumer survey playing a key role in shaping the vision. The insights gained here were crucial in aligning the solutions with the genuine interests of stakeholders (as identified through the RDW). This survey not only underscores the value of stakeholder input but also highlights their integral role in the process. While the survey primarily targeted consumers, the responses also illuminated potential areas for government intervention in the transition to regenerative systems through policy and local infrastructure.

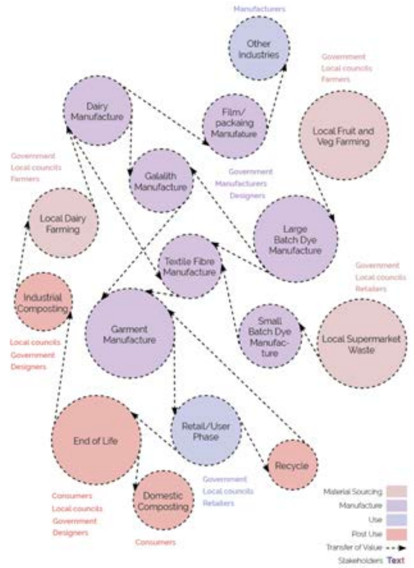
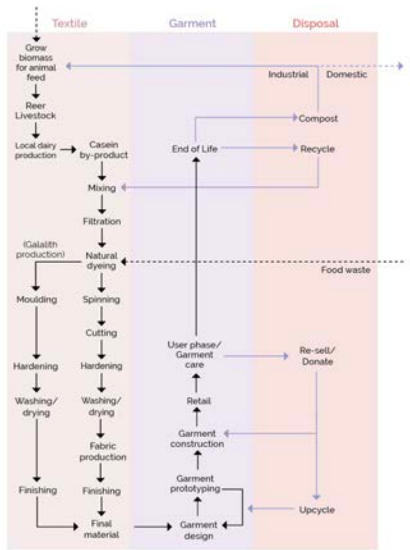


Figure 35, created in response to the vision (4.3), demonstrates the potential for stakeholder intervention and visualises what these new regenerative systems might look like. This example of a local regenerative system has been integrated into material development and decorative techniques (Chapter 5) by exploring textile dyes and screen-printing inks from food waste and prioritising creating compostable materials and design techniques. Learnings from the exploration of casein as a raw material ultimately contributed to the new lens on casein fibres and textile quality through the development of two textile sample ranges (5.3.9, 5.4.4).



These new perspectives are intrinsically linked and revolve around the example supply chain that favours local regenerative systems from food waste (Figure 136). The new perspective on casein fibres introduces a fourth generation of compostable casein-based materials manufactured using green chemistry. While these materials, due to their compostability, are inherently weaker than traditional textile materials, this creates a new discourse on the concept of disposability (high in nutrient materials) as a textile quality.

The collections of commercial and monofilament samples are central to the subsequent chapter's (Chapter 6) exploration of garment development. Learnings from this chapter inform a contemporary fashion concept based on the new lens of a fourth generation of compostable casein fibres and the new lens on textile quality, favouring a broader spectrum of longevity considering the matching of garment and material speedcycles. The creation of the design brief and the digital design of TCGs informed a more in-depth supply chain specifically for casein-based garments, demonstrating the sourcing of raw materials through to the recapture of value at various points in the supply chain.

Table 33: How each of the key gaps in knowledge played a part in answering the research question and contributed to each original contribution to knowledge.

Question/gap in knowledge	How has this gap in knowledge been addressed?	How has this informed the original contributions to knowledge?	Answering the research question
Is casein a suitable raw material to produce regenerative garments?	Through transdisciplinary material experimentation (5.2 - 5.4) and testing (5.5). Through the design of TCGs.	Material experimentation and testing have contributed to both the transdisciplinary methodology and the RDF, and new lenses on casein fibres, disposability and textile quality. A new lens on casein fibre is demonstrated through the envisioned casein supply chain. A new lens on disposability and textile quality is demonstrated through the lab-produced casein filaments and the design of TCGs.	Transdisciplinary collaboration during material development demonstrated the success of the transdisciplinary methodology. The design of TCGs demonstrated how casein-based materials can be utilised in a regenerative fashion industry whilst challenging prevailing notions of disposability as an indicator of quality.
What will these new, regenerative systems look like, and how will value be recaptured at end of life?	Through the envisioning of a local, casein-based supply chain from food waste (Figures 35 and 136)	Material experimentation and the development of regenerative systems from food waste have contributed to the RDF. The envisioned supply chain for TCGs also contributed to the new lens on casein fibres.	The development of local regenerative supply chains demonstrated how casein (and potentially other RPFs) can utilised as a raw material for fashion. The focus on compostability allows material value to be recaptured and placed back into the earth. This also contributes to the shift in material quality from the user stage to end of life.
What policies and instruments are crucial to implementing these systems?	Although policy has been acknowledged throughout the research, no specific policies have been explored in the scope of this thesis.	Although policy has not informed a contribution to knowledge, the transdisciplinary methodology can be utilised in further research to explore the role of policy in implementing regenerative systems in the FTI.	N/A
How do we ensure that the solutions put in place are in the genuine interest of all stakeholders? (Supporting people, planet, and profit)?	Through the consumer survey (4.1), interviews (Appendix 10.1) and envisioning of regenerative products and supply chains (Figure 136) using the RDW.	The use of the RDW encourages the consideration of all stakeholders when designing either products or solutions. This way of thinking has been implemented into the RDF. Stakeholders are also considered through outward facing activities such as the consumer survey which also actively contributed to the RDF.	The consideration of stakeholders throughout the research was key to understanding the utilisation of casein-based materials in a regenerative fashion system. Without the RDW or conducting the consumer survey, material outcomes were at risk of ignoring real consumer or planetary needs such as cost (people/profit), ease of access (people), ease of disposability (people/planet), desirability (people) and overall effect of material production and disposal (people/planet).

7.4 Model For Future Research

The model for TRDR demonstrates the relationship between the RDF and the TRF, indicating how the roles of each discipline are utilised through knowledge integration in response to a shared problem. Although this methodological framework has emerged from a textile-centred PhD project, it could also be adapted for other collaborative or practice-based researchers working between various disciplines. Importantly, this model emphasises the significance of hands-on experimentation in addressing complex environmental and societal challenges.

Like the model for TRDR, the RDW is a transferable tool that can be adapted and used by multiple disciplines and design or research projects. In this case, the key themes and impact areas would remain the same, whilst the supply chain and stakeholders may vary depending on the product or service. Aspects of this model can also be used in isolation; for example, the RDF and the TRF can be separated and utilised depending on the users' needs. Both tools are circular in their design to represent a flexible and iterative flow of knowledge. As with the RDW, the model for TRDR can be envisioned as a multidimensional wheel where stages, methods, and external considerations (environmental and societal) can be matched and investigated holistically rather than offering a rigid or linear format to be followed precisely.

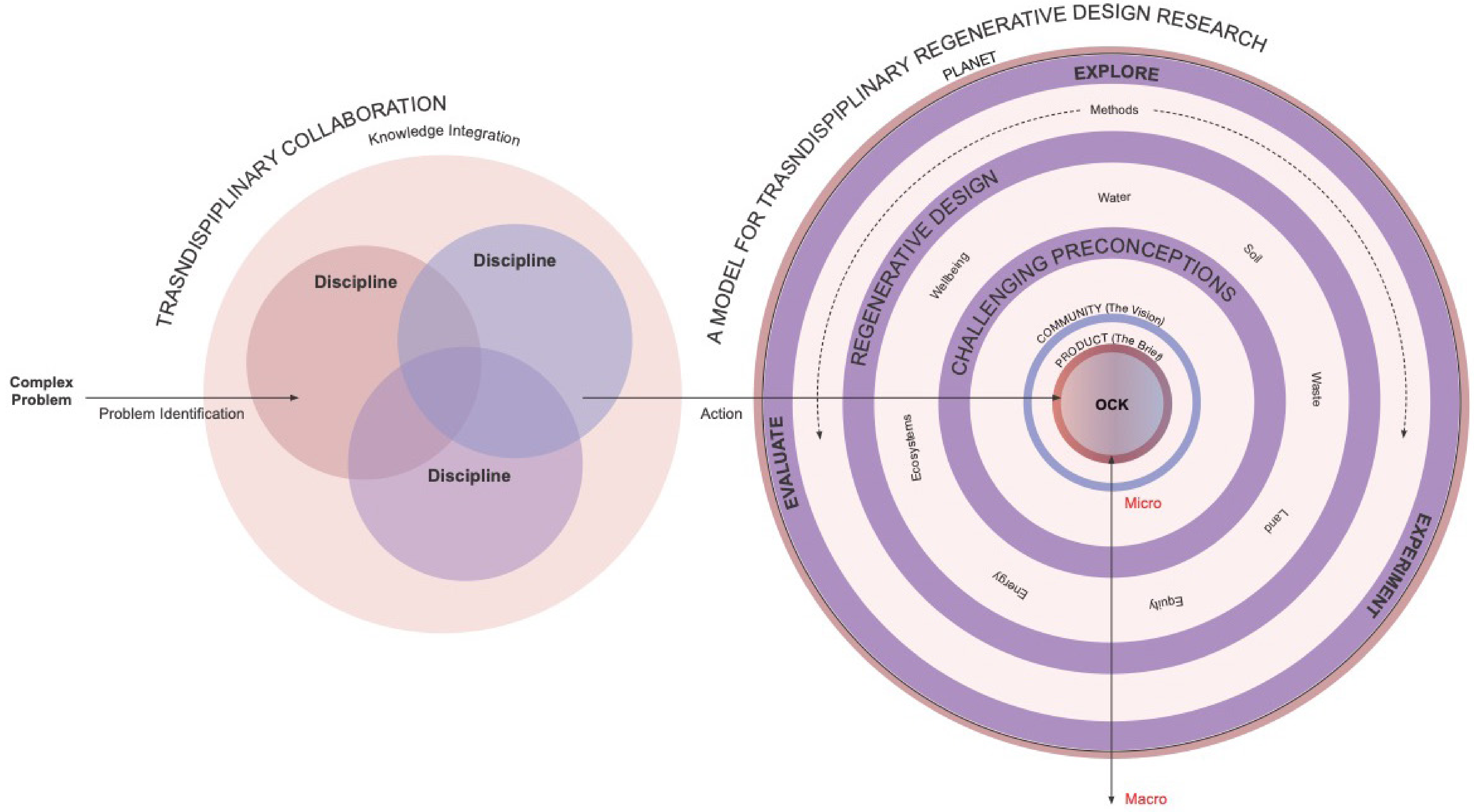


Figure 214: A transferable template for adapting the overall model while following the three stages of Explore, Experiment and Evaluate. Individual disciplines and methods have been removed as these are unique to each research project. The critical areas of regenerative design (environmental) and challenging preconceptions (Societal) are nested within the planetary boundaries and the three research stages and should be considered consistently throughout the selected research methods. The vision and the design brief are at the heart of the research, serving as a speculative roadmap to creating unique design outcomes. Original contributions to knowledge are born from a combination of transdisciplinary collaboration within the three research stages.

8

CONCLUSION

This concluding chapter offers a summary of the research outlining how the aims and objectives set out in Chapter One have been achieved. This research has demonstrated how transdisciplinary collaboration between green chemistry and textile practices can advance the understanding and utilisation of casein-based materials in a regenerative fashion economy. Simultaneously, it challenged the conventional association of disposability with poor quality within the FTI. This process involved a range of traditional and non-traditional design methods, encompassing screen-printing, textile dyeing, knitting, weaving, mono-material design, and lab work, proving that designing with the end of life in mind can be a powerful creative impulse rather than a constraint. It has been demonstrated by practice and analysis that when resources are used within the context of a regenerative economy, it is possible to create products and materials that are both functional and aesthetically pleasing without compromising compostability.

8.1 Achieving The Aims And Objectives

As outlined in the introduction (1.3), the original plan for this research was organised around three central aims and six objectives. These were accomplished through a series of practice-based experiments and outward-facing activities. As a reminder of how these aims and objects have been addressed within the thesis, Figure 7, first presented in the chapter 1 (p17) has been revisited.

AIM	OBJECTIVE	CHAPTER
AIM 1. To advance the understanding of casein fibre processing for its integration into a regenerative fashion economy through knowledge integration.	1. To document contemporary and historical textile practices concerning regenerated casein fibres and other protein-based textile materials, delineating the techniques employed and the resources utilised. 2. To map the origins and implications of disposability within the context of speedcycles and offer a multidimensional perspective on this phenomenon.	2. Informing Contemporary Practice with Historical 2. Informing Contemporary Practice with Historical
AIM 2. To establish an effective transdisciplinary methodology encompassing design, green chemistry, and archive data facilitating the generation of novel insights in processing casein for regenerative textiles.	3. To undertake a thorough critical review of casein-based materials within a regenerative design framework, incorporating principles from Living System Principles (LSP). 4. To leverage insights gained through the transdisciplinary process to guide the design and fabrication of textile artefacts that exemplify casein materials' aesthetic and functional characteristics within regenerative fast fashion.	5. Practice 1: Exploration of Casein-Based Materials and Colour 3. Methodology 6. Practice 2: Regenerative Design Thinking for Transient Casein-Based Garments
AIM 3. Critically examine and evaluate prevailing perceptions of regenerative principles and disposability as quality indicators within the fashion industry.	5. Engage with stakeholders to understand preconceptions of garment quality and critically evaluate 'the vision'. 6. To engage in a comprehensive critical reflection, drawing upon the outcomes of the evaluation process and findings, thus contributing to the ongoing discourse in regenerative design.	4. Understanding Perceptions of Garment Quality 7. Answering the Research Question 8. Conclusion

Figure 7 (revisited, p17): Research aims and objectives.

The research presented in this thesis achieved all three of its aims. The subsequent objectives have also successfully been completed. Due to multiple shifts in the research direction (due to external factors such as Covid-19 and lockdowns), some of the objectives were more difficult than others to complete. A breakdown of how each aim and the relative objectives were achieved is presented here:

Aim 1:
Aim one served as a starting point for the research and covered most of the literature review. This initial stage allowed a thorough understanding of RPFs from a social, technical, and environmental perspective. Conducting this desk-based research also allowed researchers to establish the transdisciplinary relationship as discussed in Section 7.2.1 (also contributing to Aim 2). This aim was perhaps explored in more depth than Aims 2 and 3 due to time spent in lockdown during the first year of the PhD. This time, without access to laboratory or studio space, meant that a more in-depth literature review was carried out, leading to a better understanding of the cultural implications regarding RPFs, textile quality and disposability and also led to the publication of research papers 1 and 2, which were both written during lockdown periods.

Aim 2:
Although the transdisciplinary research process was established through Aim 1, Aim 2 allowed JH and I to put this process into practice through material experimentation. The early research in material development and extended time working from home is also responsible for exploring casein-based films and much of the initial work done into colour. Colour was not initially a significant priority for this project; however, experimentation with dyed casein films led to the development of the in situ, wet-spun colouration process, which was a very successful outcome of the research.

The methodological approach combining transdisciplinarity and regenerative design was refined during this stage. A crucial element of establishing this methodology was allowing flexibility for the research to develop organically whilst facilitating the generation of novel ideas between researchers to create unique material concepts.

Aim 3:
Aims 1 and 2 combined were explored more thoroughly than Aim 3. Again, this is due to certain research limitations, such as the need to develop the ESR from scratch. As much of the physical, lab-based material development was conducted later in the project, there was less time to critically evaluate material outcomes through technical testing and social engagement. The consumer survey served as an essential source of information and guided the research regarding the vision and the design brief. Ideally, a workshop involving stakeholders from industry and academia would have also been conducted to assess the strengths and weaknesses of the vision in line with the project's outcomes.

8.2 Original Contribution To Knowledge

This research set out to provide two key contributions to knowledge. The first was a Transdisciplinary Research Methodology between the designer, chemist, and historian, allowing for genuine knowledge exchange and collaboration of equal merit. The second contribution was a design framework for a localised, regenerative fashion system that uses a fourth generation of sustainable casein fibres. This second contribution presents new discourse and a new perspective on textile quality, disposability, and casein fibres.

Table 33 (p297) also outlines how each contribution to knowledge has responded to addressing gaps in knowledge throughout the PhD.

8.2.1 Contribution One: Transdisciplinary Methodology Between Design, Chemistry and Archive Research

The research introduces a comprehensive Transdisciplinary Methodology, outlined alongside the RDF and methodology in Chapter 3. Within this framework, three pivotal stages, Explore, Experiment, and Evaluate, are detailed in Section 3.4. These stages form a continuous and iterative process that underpins the research methodology, fostering a seamless integration of diverse disciplines. Importantly, these stages align harmoniously with the transdisciplinary and Regenerative Design Frameworks, forming the basis of contributions one and two.

To effectively execute this transdisciplinary methodology, the study employed a multifaceted approach encompassing ten distinct methods aligned with its objectives. These methods included:

1. **Literature Review:** Gathering and synthesising existing knowledge and scholarly works relevant to the research area.
2. **Collaborative Learning**: Engaging in shared learning experiences with researchers from different fields to foster knowledge integration.
3. **Visual Thinking:** Utilising visual tools and techniques to enhance conceptualisation and communication of ideas.
4. **Creative Play:** Encouraging imaginative and innovative approaches to material development, problem-solving and idea generation.
5. **Experimental Design:** Conducting experiments to test hypotheses and explore new concepts, such as the design of TCGs.
6. **Lab Visits:** Engaging with laboratory settings to observe and understand practical applications and processes.
7. **Interviews:** Conducting interviews to gather insights and perspectives from relevant stakeholders and experts.

8. **Consumer Survey:** Collecting consumer data and opinions to understand market needs and preferences.
9. **Presentations:** Sharing findings and insights through presentations to academic and industry audiences.
10. **Material Testing:** Conducting tests to evaluate the properties and feasibility of materials within the research scope.

This comprehensive utilisation of diverse methods within the Transdisciplinary Methodology enabled the study to effectively address its objectives while fostering an environment conducive to collaborative exploration, innovation, and integration across disparate fields. Integrating these methods within the framework facilitated the achievement of specific research goals. It contributed significantly to advancing the understanding and application of transdisciplinary approaches within design, chemistry, and archive research, marking a distinctive contribution to the body of knowledge in this domain.

8.2.2 Contribution Two: Regenerative Design Framework

This research has established a comprehensive RDF applicable within the fashion and textile industry and across broader sectors such as academia and design practice. This semi-structured approach aims to facilitate sustainable and regenerative practices throughout the design process while allowing flexibility to explore and pivot the research as necessary. The RDF integrates these insights into the fashion and textile design process by drawing inspiration from Goldsworthy's concept of speedcycles (3.2.3) and historical design methods (6.3.1). By aligning material properties with garment lifespan, the framework offers a systematic approach to creating designs prioritising material compostability and responsible end-of-life considerations while eliminating the use of virgin raw materials from material processing to garment design.

Through the implementation of the RDF, this research has contributed three significant insights:

1. It has offered a novel perspective on textile quality by redefining it regarding a garment's life cycle and end-of-life implications rather than solely focusing on immediate user experience.
2. It has challenged traditional beliefs about disposability, proposing that disposability can be considered a facet of textile quality through composting and providing nutrients to the earth while encouraging a re-evaluation of societal engagement with garments.
3. It has advanced the discourse on casein fibres by positioning them as part of the fourth generation of RPFs developed through green chemistry.

Nested within the Transdisciplinary methodology, the RDF has been informed by various disciplines spanning design, chemistry and history. This multidimensional approach provides a holistic perspective, enriched with diverse viewpoints and tacit knowledge, ensuring a more nuanced and inclusive process to sustainable design practices.

Traditionally, sustainability efforts have predominantly focused on a 'design for recyclability' approach due to the sheer scale of the environmental damage created by plastics (1.1.2). However, regenerative systems have often been overlooked in design considerations. This research emphasises the importance of designing for regenerative systems, highlighting their significance in addressing larger environmental issues beyond recyclability and plastic waste. Instead, it underscores the need to shift focus towards creating designs and systems that actively contribute to the restoration and regeneration of ecological balance.

A New Lens On Textile Quality

This research proposes a fresh interpretation of textile quality by shifting from evaluating a garment's quality solely based on its performance during its useful life to considering its end-of-life implications. Unlike conventional approaches that primarily emphasise durability, aesthetics, and user experience during wear, this perspective examines how a garment's life cycle can reflect alternative forms of material quality*. By drawing from Goldsworthy's examination of speedcycles (2017), the research explores the possibility of intentionally designing trend-driven garments meant to last for a specific number of uses while remaining easily disposable in a responsible manner. This paradigmatic shift challenges traditional notions of textile quality, urging consideration of what garments and their materials can offer beyond their immediate use phase.

A New Lens On Disposability

In conjunction with redefining textile quality, this research introduces a novel discourse on disposability within the context of fashion and textiles. It challenges the prevailing belief that slower fashion, characterised by longevity, inherently equates to superior quality and improved sustainability. Instead, it critically examines our societal engagement with garments, questioning whether disposability could also be considered a facet of textile quality. By proposing this shift in perspective, the research encourages reflection on how garments are presently used—for short-term or long-term purposes—acknowledging that disposability can be a legitimate criterion in evaluating a garment's quality and environmental impact when used with the appropriate materials.

A New Lens On Casein Fibres

Reframing quality and disposability in textiles introduces a distinct perspective on casein fibres. Casein fibres, a naturally compostable material abundant in nutrients yet possessing comparatively lower strength properties, are repositioned within this research as an exemplary instance of a regenerative, mono-material archetype. Unlike previous explorations in history (2.2), this research pioneers a novel integration of casein-based materials to facilitate the creation of fully compostable or intentionally disposable garment archetypes. By considering casein as the primary source for textile fabric, components, and coatings, this research breaks new ground in envisioning and implementing a holistic approach to garment creation, comprehensively addressing environmental sustainability and end-of-life considerations.

Each of these points collectively emphasises the significance of the RDF developed through a transdisciplinary approach, offering new perspectives on textile quality, disposability, and sustainable material development while advocating for a shift towards designing for a regenerative economy in the face of pressing environmental challenges. As with the nature of this thesis, these new lenses have not been developed in isolation and have informed each other throughout the research.

Each perspective is unique due to its departure from conventional notions in the FTI, challenging established paradigms by introducing new criteria for evaluation and the utilisation of materials like casein in garment production. The research opens doors for innovative approaches towards sustainable fashion and material utilisation, contributing to a broader conversation on redefining quality and responsibility in the textile industry.

Considering these two contributions to knowledge, the TRDR model was developed (7.2.4) to demonstrate their transferability and applicability to future practice. This model reflects how the Transdisciplinary Methodology filters into the core of the RDF, allowing a multifaceted approach to problem-solving through regenerative design.

A primary example of how the TRDR model can be applied is through the sustainable colouring of casein-based materials using anthocyanins (5.4.3). This example is used as proof of concept for one of many possible future outcomes within these novel contributions to knowledge. Knowledge integration through the literature review and early material experimentation with colour and casein led to the initial idea of colouring materials during the dope or wet processing stage. Although the Transdisciplinary Methodology made this research possible, it was inspired by the regenerative aspect of the study in line with the critical themes of regenerative design.

8.3 Impact On Industry

This thesis highlights several points resonating across the fashion and textile industry, spanning into agriculture and the development of a local, regenerative economy. This section discusses the potential impacts on various sectors and key learnings for designers:

Holistic System Creation And Collaboration

Transitioning from fossil fuels and reducing dependency on virgin raw materials requires collaborative efforts across sectors. This shift can influence not only the fashion and textiles industry but also agriculture, manufacturing, and local economies. Designers, scientists, engineers, and industry experts must collaborate closely to develop sustainable materials tailored to specific design needs. This collaboration can foster the creation of unique, regenerative materials and garments while minimising waste and environmental impact.

Challenges And Trade-offs

Exploring natural dyes like avocado dye offers opportunities for enhanced material properties. However, variations in quality, colourfastness, and interactions with fibres pose challenges that demand comprehensive investigation for large-scale production and environmental sustainability. As with synthetic dyes, careful assessment of the environmental and economic sustainability of natural dye production is essential, considering both benefits and challenges.

The same goes for RPFs. Casein has been used as an example raw material in this research; however, emphasis should be placed on what appropriate waste sources are locally available. The FTI must become less reliant on the same few materials and processes and adopt a more flexible approach, allowing for the development of novel materials based on supply and demand.

The Transition Towards Regenerative Practices

Adopting a design approach that aligns with material and garment speedcycles represents a significant shift towards regenerative practices. This approach involves reconsidering garment design processes, utilising mono-material production, and exploring innovative construction techniques. Tools like the Regenerative Design Wheel can facilitate the critical evaluation of new design and manufacturing practices, enabling a shift towards customer-centric and environmentally conscious fashion.

Legislation And Responsibility

Industry and consumers need more responsible options for textile disposal. Encouraging legislative changes for responsible waste disposal and encouraging a circular economy approach that encompasses compostability and recyclability can significantly impact sustainability efforts.

Transitioning the fashion industry towards biobased raw materials from food waste presents a multifaceted set of challenges: The industry would need to invest significantly in research and development to optimise production processes and improve efficiency. Managing the supply chain and logistics for sourcing food waste as a feedstock would require extensive coordination and infrastructure development. Clear regulations and ethical frameworks must be established to prioritise food security and prevent competition between food production and raw material sourcing for fashion. Adapting to an entirely new feedstock necessitates reimagining traditional manufacturing methods and supply chains, requiring substantial investment and retooling of existing infrastructure. Collaboration between stakeholders, technology innovation, and consumer education is vital for successfully navigating these challenges and steering the fashion industry towards a regenerative future.

8.4 Challenges Of Transdisciplinary Research

Although many of the challenges associated with this PhD have been discussed throughout the thesis, this section highlights the main challenges encountered from a personal perspective due to the transdisciplinary nature of the project.

Engaging in transdisciplinary research has been an exciting yet challenging journey. Integrating knowledge from diverse fields meant dealing with an abundance of new information whilst navigating through diverse scientific literature and methodologies. Synthesising this new information into a coherent framework for design-related outputs was initially very difficult and often overwhelming. Converting intricate scientific terminologies into a more universally understandable design language also demanded considerable effort and time.

The sheer scope of insights gained across multiple disciplines posed another challenge: deciding what to include in the thesis and avoiding an overload of technical details took much consideration. The ever-evolving and multifaceted nature of research added another layer of complexity. Determining the cut-off point for new research contributions and incorporating ongoing work into the thesis was challenging. Integrating recent laboratory results and co-authored papers necessitated careful consideration to ensure the thesis remained as streamlined and cohesive as possible.

Amidst the complexities of navigating different disciplinary perspectives and ongoing developments, staying focused on the ultimate objective became paramount. Balancing these intricacies while keeping the larger goal in sight became a fundamental aspect of the transdisciplinary research journey.

8.5 Future Work And Opportunities

This final section discusses what questions remain unanswered and presents opportunities for future work. The broad range of topics and practices covered in this thesis provided a comprehensive overview of what could be achieved within the project. Due to the complexities of the transdisciplinary nature of the project, many areas of interest were uncovered; however, not all of them could be addressed within the timeframe of the PhD, leaving a wide range of scope for further exploration and development.

Galalith: Galalith was briefly explored in the early stages of material development (5.2.1) to understand casein in its rawest form. Extracting casein from store-bought milk allowed me to form a tacit knowledge of pure casein before experiencing it as a textile material. Although some basic experiments with shaping and setting casein in this form were conducted, it was challenging to delve fully into this practice area without additional equipment or facilities. For this thesis, learning about the manufacturing process for galalith is all that was required and delving into a full-on investigation to develop a green manufacturing process was unnecessary. Although there are versions of eco-friendly 'milk buttons' on the market today (Codelite, n.d.), there is scope to further develop green methods of producing galalith for other textile components or fastenings, as well as replacements for other forms of plastics in fashion products such as shoes or accessories.

Films: Films were initially developed as a faster way of testing casein formulas, which could then be applied to textile filaments. Although research into casein films was used as a placeholder, the research showed much promise and could be applied to other industries, such as biodegradable or water-soluble packaging (mainly food products) and textile coatings and glues.

Fibre Processing: As discussed throughout this thesis, two critical areas for further development are fibre processing and the testing of green cross-linking agents. The wet spinning of casein monofilaments happened later in the project than anticipated, leaving little time for a thorough investigation in this area. During his research with casein films, JH explored citric acid as promising cross-linking agent; however, this alternative was not tested during spinning due to time restraints. Now that the basic formula for casein dope has been established (5.4.1) and the ESR is in working order, the next stage of this research is to continue the exploration of alternative cross-linking agents to develop a textile fibre which is durable enough to create a 100% casein woven material.

Another area for exploration at the fibre processing stage is spinning casein fibres into yarn. The materials produced in this research have been made by hand at lab-scale, meaning that their properties are not comparable to the commercially available casein fibres or textile materials. This was not the overarching goal of this research; however, spinning lab-produced filaments into yarns allows an opportunity to test the physical properties of the material before weaving, allowing opportunities to tweak the spinning process and casein dope accordingly.

Wet-Spun Dyeing: In response to fibre processing and the creation of an in-situ colouration process, further development is required to identify a green cross-linking agent that provides strength while working harmoniously with natural sources of colour from food waste. While the dye trials conducted in this thesis provided positive results, Ex 15 (5.4.3) did demonstrate degradation when used directly in the dope through the dulling/browning of the dyestuff. It would also be beneficial to test other forms of food waste as dyes (as was done in the dye tests with commercial casein fabric, (5.3.1) to find a dope-dye system that is more resilient and can withstand the conditions of the casein dope.

Testing avocado dyes and other dyes containing natural tannins would be an interesting starting point for further exploration. Tensile testing showed that dyes containing tannins could influence material strength (5.5.1), making them a possible option as a natural cross-linking agent and a source of colour.

Material Testing: Further testing surrounding compostability and degradation of casein-based materials is necessary. Following the series of tests conducted in this area (5.5.2, 5.5.3), it is recommended that plant response testing be carried out on lab-produced casein filaments. It is also recommended that each test be conducted on both undyed and dyed lab-produced casein filaments (containing a green cross-linking agent) to compare degradation times and the resulting soil quality.

Woven Material: The consideration of textile construction can play a huge part in the design of TCGs. A pre-made fabric is typically selected to best fit a garment's aesthetic and performance requirements. However, working directly with textile developers to weave tailor-made solutions into materials is essential. Now that the ESR is complete and able to produce casein filaments in larger quantities, there is a great opportunity to continue developing both casein filaments and woven samples simultaneously.

Garment Design: Due to time limitations, the toiling of casein-based garments was only partially explored as an insight into alternative design techniques within a regenerative and mono-material design framework. Going forward, there is scope to build upon this research and investigate more technical design and production methods such as whole garment knitting and weaving.

Consumer Studies: Future research endeavours could focus on conducting longitudinal studies to observe the behavioural changes in consumers and the industry over time. Additionally, collaborations with marketing experts, psychologists, and economists could shed light on the drivers of consumer choices and the effectiveness of communication strategies in promoting regenerative and mono-material fashion. Furthermore, conducting pilot projects with brands and retailers to implement and assess regenerative practices in real-world scenarios can offer valuable insights for scaling up sustainable initiatives across the industry.

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APPENDIX

10.1 Interviews

Hannah Auerbach George, and I conducted the three interviews presented as part of our research for the WP6 industry report. While these specific interviews may not be directly cited in the thesis, they played a crucial role in providing insights into essential aspects of our research. Each interview has been transcribed and edited for clarity.

10.1.1 Joanne Silverstein & Julia Meyersohn, Dispo

Hannah Auerbach George conducted this interview on the 9th of December, 2021. Liz Tregenza from the V&A Museum and I participated as facilitators and note-takers during the session. The insights gathered from this interview were utilised in the paper entitled 'Challenging Perceptions Of Fast And Slow In Contemporary Fashion: A Review Of The Paper Dresses Trend In The United Kingdom And The United States During The 1960s' (2023). The interview features Joanne Silverstein, designer and co-founder of Dispo, and Julia Meyersohn, daughter of Diane Meyersohn, the designer and co-founder of Dispo. Dispo was one of the largest manufacturers of paper dresses in the UK during the 1960s. The primary focus of this interview lies in exploring the social and cultural context of the 1960s paper dress fashion trend, along with examining the materials and processes involved.

Hannah: Hello, I'm Hannah, this is my colleague Liz at the V&A, and then Marie from LCF, and you're happy for this to be recorded? I sent Julia some forms about consent, you've got them?

Julia: Yeah, I have them. What would we do? We'd sign them, and can I just email them to you?

Hannah: Yes, that would be fantastic. The first one is just a participant information form. It gives you a bit of background about the project. The second one is a consent form, which you can fill either the yes or no column to say if you're happy for us to quote you if we were to write papers and so on, any details in it that you're unhappy with, just let me know and we can change them. If you're happy with all of that, we can get started on the questions.

Julia: Yep. Brilliant.

Hannah: Why did you decide to start Dispo? Were there many other examples of paper dress manufacturers at the time? Or was it something completely original that you came up with?

Julia: So obviously, you (Joanne) started with my mum (Diane).

Joanne: So, we started with both us ladies who had been working and had young children and were at home and we decided we wanted to do something, go back in business. We weren't going to be content with spendng the rest of our lives at home.

Julia: Which was very unusual at the time. Most people were housewives, really.

Joanne: As far as other manufacturers of paper dresses, there were, but I think if you check with the V&A, you'll actually find those examples there. I don't know the names.

Julia: Not in England, I don't think; there was one in America.

Joanne: No, no. But there was an exhibition with the V&A, and they did have other dresses there, so I'm sure they have them in the file somewhere.

Hannah: So maybe to clarify a little bit, the second part of the question is: what made you come up with the idea of paper as a medium?

Joan: It wasn't exactly paper. I mean, I do think, in our case, it's a misnomer because it was actually a bonded fabric.

Julia: It was washable.

Joanne: In other words, it was a bit like felt, except it was the chemical it was made from.

Julia: We've got examples of it here. And so, it's, it's definitely got quite a good strength to it. I don't know what you would compare it with nowadays. Have you been able to touch the ones in the V&A?

Hannah: Unfortunately, not, because all of the pieces are inaccessible at the moment.

Joanne: Because they were actually in the fashion collection for years and years. And then it was at the Museum of Childhood. I don't know if you saw the children's ones. There's a whole children's section there as well.

Julia: I've got quite a lot here at the moment, and we've actually got sample sheets as well because they must have gone somewhere like Premiere Vision to choose the fabric. I remember my mum talking about it, and obviously, the textiles were more mum; my mum designed the textiles, often going into the V&A to get her inspiration. So, some of them are kind of inspired by Islam and using really bright colours. So I've noticed Liz is wearing a really sort of vibrant, 60s inspired dress, but, in those days it just didn't happen for these sort of colour combinations, which, they're really kind of vibrant.

It just wasn't happening at the time. So, I think we forget now how cutting-edge it really was. I don't think Joanne even realizes how incredible it was to do what they came up with at that time in history. You know, people weren't aware of even thinking in those terms of throw away.

And I don't know how they came up with it. I think it was a collaboration between my mum and Joanne, just as you do when you're setting up a company. I think it went hand in hand with the start of faster fashion. I remember as a child going to Bieber all the time. People were thinking very differently that they'd buy an outfit just for the night to go out to a party, and again, it never happened before because it was much more couture-based. But there was a lot of very simple, glitzy jewellery that went with it.

And I also have these packets of disposable jewellery that they designed so you could actually stick that on your body. There's a great picture of them when they were about to head off to New York. Yeah, oh, look at

you (referring to a photo of Joanne and Diane). My mum with their suitcase about to go to New York to sell their collection.

Hannah: Well, my next question is; what was the motivation behind the brand? I feel like you've covered that a little bit, but maybe to summarize, you're basically trying to create something very exciting and new and something that maybe appealed to a single use market.

Joan: No, I'm sorry to interrupt.

Hannah: No, please.

Joanne: Well, I guess I don't think we actually did want to do throwaway, particularly.

Hannah: Okay. So could you maybe explain a little bit why you were drawn to that particular material? Was it a cost? Was it the colour?

Julia: I think it printed really well, unlike paper, which other people were exploring. It didn't rip. You could cut it easily and print it beautifully. And you could wash it two or three times. So we've got some samples here of fabrics, which were printed. Yeah, it just printed really well. There was no bleed on it. You could wash it. The colour didn't change.

Joanne: I did go beyond the dresses, you see, where I actually was asked to design an apron, for instance, for a Wendy's hamburger place. So, we would think about doing other things besides just dresses.

Julia: I've got a pantsuit, like an all-in-one pantsuit. I've got lots of mini-skirts. My mum must have done their last sort of marketing for Dispo with them, I remember their Union Jack flag and everything with a little picture of them. Again, you know, everything was short haircuts, and like even this, I think it's fabulous. I don't know if my father wore it, but it's a massive kipper tie, which is just really cool. I wouldn't be surprised if my dad did wear it because he was pretty outrageous. So yeah, it was a time when men were starting to get a bit more fun and experimental and also, men and women were wearing the same clothes, that was all happening as well.

And I really like the way that they use very simple attachments. So the top of the mini skirt is a very simple rope just to tie it, a nice little rope just to tie it in if it needs to be cinched at the waist. Very simply made. What was also amazing about it was you could customize it. People could buy it, and they could cut it, and you didn't need to seal it. This one has actually got a little slit in, so I don't know whether my mum wore it to a party and then just said, oh, I'm just going to make it a little bit higher or have a little, you know, thing coming on the side. So yeah, it was customized and really easy to do yourself, which is such an incredible quality of any garment, to be honest. We'd all like to be able to do that with most things.

Hannah: That was one of my later questions; if you had any examples of clients actually customizing their own outfits? It sounds like that regularly happened?

Julia: I think it really did. And I think that's what they wanted to make and to make that available to people. And I can imagine my mum thinking that was really lovely because she was very creative. So she would have loved those people customizing everything. It looks like some of the fabrics are from America, quite a few of these are from America. And I think they love the DayGlo quality. Again, DayGlo and things like that, it was quite new in those days. Very Carnaby Street.

Hannah: So, the next question would be, how was the paper textile constructed? You talked about it being not quite paper, it being more like a felt material that was bonded. And so, what was your involvement in that process? Did you ever have any engagement with the factories, or did you buy it on the roll?

Joanne: We just bought the basic fabric from the company and sent it to the printers.

Julia: So it would've been printed, probably silk-screened.

Joanne: No, I think it was roller printers.

Hannah: Do you remember the name of the company?

Julia: We were very East End. Yeah, it was a sort of an East End sweatshop, I think. So, you know, things were being produced in England then.

Joanne: They probably still are. We had to carry everything there and carry it all back, huge rolls of fabric.

Julia: But my mum, she did a lot of the fashion drawings, didn't she? I've got some really lovely fashion drawings that she did. I've got them on; they're all on slides. Which is always hard to show.

Hannah: So, she did some of the fashion drawings, she designed the garments. Who was making the garments? Who was putting them together?

Joanne: I don't know who, actually, I can't remember the name of the factory.

Hannah: But you would outsource to another company to put them together for you.

Joanne: We had to carry all the fabric down there. They cut it and sew it up. Everything was a cash business.

Julia: And, your studio, your workshop where you were working was at Riding House. Riding House Street, which is very much the garment industry. Well, I don't know if it is anymore, but it certainly was where all the wholesalers were. And that's where their office was. But yeah, I don't know if she (Diane) designed every single fabric, but she certainly did quite a few of them, didn't she? Because that was her background. She was an illustrator and graphics designer. So I think she did most of that side of things. And then Joanne's husband photographed them. The models. So it was a real collaboration between people who had, you know, high, good skills.

Hannah: My next question was who was buying it? who were you selling it to, and who was wearing these dresses?

Joanne: Well, teenagers mostly.

Julia: Yeah, young people. All us kids wore it. Joanne has two daughters. I certainly had a very, I mean, I was

only about three or something, two or three, but I remember wearing it. I probably didn't want to, but I mean, I was very little. Joanne's daughters were slightly older. And there's a photo of your daughter wearing one of the outfits.

Joanne: Yeah, when she was little, but it doesn't necessarily mean that they were okay for kids.

Julia: Yeah, there's a very sweet little dress here (referring to a photo).

Hannah: Oh wow, look at that. It's gorgeous.

Julia: Yeah, it's great. Lovely colours. So that's really a sweet little one (dress). I think this one's in the Museum of Childhood.

Joanne: But we would stop selling this because there are more precautions, I think, with young children. You know, it was still flammable. So, with young children, that was a no, no.

Hannah: Yes. So, one of my questions was also about the kind of fabric and the colours and the way you were working suggests a teenager or a young woman in mind with lots of the styles, but then you obviously still had this children's range and, I was wondering what the motivation was to go for children.

Joanne: It was more exciting. Yeah, it could have worked if it were really allowed because, you know, the government said no, no. It'd be perfect for party dresses, you know? Pick up a thing and throw it away. Don't spend a lot of money on a party dress, you know? But unfortunately, there was no sort of fireproof finishes or anything you could do without making the fabric really stiff.

Julia: And they also collaborated with the designer, Wendy Ramshaw. She did some of the jewellery at the time as well for them. I think Mum used to have some really lovely jewellery, very simple kind of laser-cut acrylic, big pieces. But as far as how hard wearing it's a really tricky one because it's the usual story. It's how hard do you party when you wear it?

Hannah: I was wondering, you were talking about how you had a pantsuit because I feel like a dress might be more forgiving.

Julia: But you would feel confident walking around in the pantsuit; they wouldn't tear, and it was quite strong. It's quite loose, it's flared trousers, the ones that Joanne's got here, it's, it's a beautiful outfit, and I wish I had that one because I'd actually wear it now. It looks really comfy, it actually hangs really well as well, you look amazing in that.

Joanne: It was strong.

Julia: And it did hang, and it had a sort of structure. Actually, when I went to the V&A show with Joanne, which they had about 12 years ago, there was a big party there at the opening, and I wore it to the show, which was really fun because it was actually in the cabinet there and everything.

And that was the first time I've actually worn it out. And it was great because it has quite a lot of good structure to it. So, it is comfortable. There's no doubt about it. I mean, obviously, it would probably be changed.

Now you'd be able to do different things. You know, you're doing a PhD in materials. So, I'm sure things have moved a lot further on that side of things.

Hannah: So, then we were wondering about the phase-out. Why was the company finished? Did you just decide you wanted to finish it, or was it reactive to the market? Can you explain a bit more?

Julia: It usually comes down to money, doesn't it?

Joanne: It comes down to money and the fact that it was really, lots of fads, they come and go, and they're very big for a little while, and then they disappear. I do think one thing would have made a difference, if we'd had social media at that time, and it had been on Instagram or something, it would have blown up. But don't forget at that time, young kids, they don't look (at newspapers), so we'd have newspaper pictures for a bit of publicity, but young kids don't read newspapers. And magazines, occasionally they might look at a magazine at that time. So how did information get around? It got around by word of mouth. So that was one of the key things.

Hannah: Do you think it's fair to say access to your market was difficult?

Joanne: Yeah, I would say.

Julia: And they must have done a bit of advertising because I've got this photograph from Dunlop, so they use the mini-skirts here as advertising. In fact, that's the tie there as well. So that's pretty much what came in. It's called Get Gear. That was some promotional thing that was used. So yeah, I don't know. It's hard to know when it or why it ended.

Joanne: I think it was money.

Julia: Yeah, I think if you're not making enough money, you don't know how much to put into a company. And, of course, I'm afraid it is also true that mothers didn't leave and go off when they had young children in school and things and with the dad's working, the mum has to tend to be there at home. So it's not the same as now, where you can have a full career, unless you had an au pair all the time,

Joanne: Which we did.

Julia: You had an au pair, yeah. But potentially not as free as you would have liked to continue the business. You might have just gone off, could you? If you needed to go off to America to sell.

Joanne: Oh no, no. It was much more constraining then. It was very constraining when you were little; we did spend time trying to persuade companies to invest in us. And we would go to, say, I've forgotten the name of it, the big company that makes paper napkins, or rolls. Scott Rolls. And there was a few women coming in at that time. And we would sit and give them our business plan, saying, if you use one of your machines to cut it instead of hand cutting, how easy it would be, all you have to do is stamp it out, and they'd sit there and smile and look at our legs. In other words, they'd look at us.

Julia: It's very sexist.

Joanne: You probably can't believe it, but I mean, that was it, you know.

Julia: Tell the story about going to New York.

Joanne: Oh yeah, the London Fashion Council sent us to New York with a bunch of other young designers. And I told my partner, oh, it's going to be really cold in New York, let's take lots of warm clothes. And it was like 90 degrees and we had nothing else to wear except the dresses. And, of course, she (Diane) is very tall, and I'm very tall. So we had to go to the ambassador's lunch or whatever, the party for the group. And we were in these tiny dresses which just covered our bum, just about. So that was it. We would get a dirty look, you know, from the ladies that be.

Julia: Because, I mean, America was so conservative then. But in New York, mum said she had stones thrown at her and stuff in New York. She said people were really, just not wearing any mini-skirt, not even just the paper dresses, that people were not like in Carnaby Street. It wasn't as advanced.

Hannah: That sounds like you were quite a bit ahead of your time, perhaps. You were real pioneers of that sort of look.

Julia: I think you were really ahead of your time.

Hannah: So finally, I just have one other question about the disposal of the garments. Do you have any idea what people did with them? Were people likely to treasure them and try to keep them for as long as possible? Or were they quite commonly chucking them in the bin? Do you know anything about that aspect?

Julia: I mean, I'm just saying we've kept ours. They've lasted, but they've been put away, obviously. They haven't been out so I think that's a tricky one.

Hannah: Yeah, that's fair enough.

Julia: Yeah, I don't know if we can answer because we don't know where they all ended up.

Joanne: People didn't have any conscience about throwing things away. Compared to today when you're getting all the messages like, you know, conserve, conserve, and don't throw things away.

Julia: Have you been to the Fashion & Textiles Museum where there's a show, a 60s show at the moment?

Hannah: Liz is nodding, so she must have seen it.

Julia: There's a film footage showing a paper dress. It's not my mum's one. I think it's the American one, and it's a photographic image on the dress. And the advertising for it actually shows her sunbathing in the park. She whips off her paper dress and there's some man there looking very conservative looking at her, you know, and then she throws it. Oh no, he throws it in the bin, and I'm thinking, now you would never do that where you throw something in the bin. So it just made me think that, actually everybody just chucked everything in the bin and that's why we're in such a problem now. But I think it was interesting to see, so maybe go and have a look at that. It's at the Fashion Textiles Museum, the Zandra Rhodes one.

Hannah: Actually, I do know the clip that you're talking about because I think at the end of it, she sort of just shrugs, and then she gets another one out of her bag and pops it on again. Yeah, it kind of says something about the mentality of the time. I don't know if Liz, you have any questions you want to ask.

Liz: It's just absolutely lovely to hear you speak about the time and your experiences and also about the garments so passionately and to see how, I mean, I'm really amazed by the survival of the colours now that you're looking at those textiles like 50 plus years on, and the colours haven't faded at all, which I think says something really interesting about the qualities of that fabric, that the textile that was used hasn't faded at all by the looks of it like.

Julia: Yeah, absolutely. I don't think it has faded at all. It's not something that just comes off or anything. It doesn't rub off. I think if it was submerged in water, which I'm not going to do, it wouldn't start to, you know, where you can buy a lot of things that do. I think it would really still be very resilient even today. But I do think there are other versions now which might feel a bit softer that might be a bit more tactile than this because it has got a sort of roughness to it. But maybe that's what made the print stay so well that it has a slight texture to it.

Liz: Because I haven't handled a Dispo one, but I have handled other examples in a previous job role, and I do know what they feel like. The closest thing I can think of is a Vilene?

Julia: We think it is a type of Vilene now.

Joanne: That made it different. That's why you could wash it.

Liz: Yeah, that would make sense then actually as a type of Vilene.

Joanne: We were not paper. Disposable dresses but not paper.

Julia: So it's disposable, but it's obviously more substantial and that's why it could be washed and now, as I said, you could make it out of something totally different, couldn't you? Some sort of bamboo husk or something. What are you using, pineapples?

Hannah: Well, like you said, there's all sorts out there now. But I mean, it's still fascinating to look back at the first people doing this sort of thing and see what your mentality was.

Julia: Also, when you look at the design of it fashion-wise, it still looks good, you know? It's A-line dresses, you don't see much difference if you look out now, you know? And that's what I always find incredible. And obviously, fashion comes back and all. It's definitely passed the test of time, it really has in that respect. And I mean, I just think it's an incredible thing that you achieved (Joanne), I really do think it was incredible.

Joanne: I think it was a very creative time period, let's put it that way. Yeah, it was very good. And you were surrounded by other creative people, and it just made you think.

Hannah: Fantastic. And I just noticed we have a minute and a half left, and I was just wondering what you did after Dispo? Did you do anything else creative business-wise?

Julia: My mum did illustration all her life, really. So yeah, I mean, I'd like to make it more of a collection of work because I think there are a lot of different sides to it. Like the fashion illustrations that my mum has got are so gorgeous. And I've always said I'd get them printed up at some point. But I'd like to see the collection show other sides of it, like, I noticed there is some of the jewellery in the show. Well, there was at the V&A, there was some of the jewellery there but, I don't know, it would just be nice to see all the other things; I mean, also the fashion photos are incredible that Joanne's husband took.

Hannah: Is there anything else you want to add in the last minute before we go?

Julia: No, it would just be nice to be kept in the loop with everything. Obviously, I'd like to show Joanne and read anything that's written.

Hannah: So we will, of course, keep you in the loop of whatever we go on to write, but thank you again so much. It has been really, really fascinating, to speak to you both.

10.1.2 David Courtney, Courtney & Co

This interview was conducted with David Courtney from Courtney & Co button manufacturers on the 14th April, 2022. Courtney and Co offer a range of casein-based buttons under the name Codelite, mixing heritage crafsmanship with novel materials. The aim of the interview is to gain a modern perspective on the use of Casein in contemporary fashion and textile products and to gain insight into the manufacturing processes used.

Marie: Great. As mentioned in my email, this interview contributes to both my PhD thesis and an industry report exploring the commercial potential and environmental impacts of regenerated protein materials, with a focus on casein. You'll have the opportunity to review and approve materials before publication. Feel free to reach out if you have any questions.

David: Of course. Thank you. Appreciate it.

Marie: Thank you again for participating. Our previous conversation was intriguing. Let's touch on some company history. In our last discussion, you mentioned acquiring the last horn button manufacturing equipment in the UK. Please could you share a bit about the company's background and why you chose casein over other materials.

David: Behind me, you can see the James Grove Heritage Center in our factory, featuring one of the logos used for many years. James Grove initiated the button factory in Halesowen, West Midlands, in 1857. The company collapsed in December 2012 after 155 years of continuous trading. Initially, they specialized in hoof buttons and later ventured into horn by mistake, becoming pioneers in horn button production. Casein, perfected by an immigrant named Victor Schutxe in Stroud, Gloucestershire, around 1909-1911, became a significant focus for the company.

The casein production process mirrors cheese-making, starting with ordinary dairy milk, sourced from Ireland for our blanks due to its richness in fatty proteins. Renit, a natural enzyme, separates solids from liquid whey, leading to a semi-solid material. The whey finds applications in various industries. Acetic acid turbocharges the process, reducing moisture over time. The final step involves a formaldehyde or formalin bath, containing a small amount of formaldehyde, a naturally occurring gas. This process doesn't make formaldehyde intrinsic but a part of the finishing, hardening the material.

Let me explain the extrusion process, where moisture is removed, and layers are added over weeks, gradually building thickness. Casein's versatility allowed its use in many products including knitting needles, spectacle frames, and buttons.

Marie: Fascinating. Considering historical use and applications, do you see casein's popularity growing today, especially with its biodegradability and sustainability?

David: We stand at a unique juncture. The cost dynamics have shifted due to increasing oil prices and the rising cost of livestock holding means. While the gap between casein and alternatives narrowed for a while, recent trends favor casein, driven by those valuing sustainability, biodegradability, and environmental responsibility.

Marie: Your emphasis on biodegradable buttons aligns well with these principles. Can you assure the safety and non-toxicity of the colours used in your buttons?

David: Indeed, it is a lengthy process. For instance, take a button like this; it's about four or five millimeters thick. That's approximately five weeks of setting time. So it's not an instantaneous process. This sheet here is essentially 96% milk. It's incredible. Picture it like layers; each time they add a bit more, it solidifies, building up thickness. Another form is rods, which can be cut into sections or used as a primary material for various applications. Initially, knitting needles were made from casein rods instead of sheets.

There's a company, Banton Frameworks, that crafted my spectacles. They make frames out of milk casein. They source antique materials, buying them from places like France, where leftovers from old warehouses are found.

Marie: That's incredible. Historically, casein was used in various things like jewelry. However, glasses made from it are fascinating. In today's context, do you see casein gaining popularity?

David: We're at an interesting crossroads. Casein allows pigment introduction at any point, providing versatility. Reflective buttons imitate mother of pearl, and there's even tortoise shell made of milk casein. After World War II, the demand for casein declined with the rise of cheaper alternatives like nylon and polyester. However, recent trends in increased oil prices and rising costs are reviving interest in casein due to its biodegradability and sustainability.

Marie: That's great, especially with your emphasis on biodegradable buttons. Going back to colour, can you assure the safety of the dyes used in your buttons?

David: Absolutely. We adhere to the Oeko-Tex standard, ensuring that all dyes used are safe and non-toxic. When it comes to finishing, we use various natural materials like wooden pegs, porcelain pins, walnut shells, and maize husks. With milk casein, we possess a certificate affirming its degradation to 60% within six weeks under laboratory conditions, meeting EU biodegradability standards.

Marie: That's reassuring. Did you encounter any challenges with equipment and machinery when you initially took over the factory?

David: Indeed, when Grove collapsed, we responded to a call to save Britain's horn button industry. We bought machines, representing the necessary variety for production. Initially, we leased them out to a third party, but due to unforeseen circumstances, we ended up learning how to operate them ourselves in 2016. It was a challenging yet optimistic venture.

Marie: Waw, that's interesting. It sounds like things worked out for the best.

David: Absolutely, they are well received. The uniqueness and the story behind the buttons draw attention. People are genuinely intrigued by the materials and the processes involved. When we attend trade shows, we see a mix of reactions. Some are purely captivated by the story and the natural origins, while others are driven by the desire for sustainable and traceable materials. It's not just about selling buttons; it's about conveying a narrative and sharing the journey from raw materials to the final product.

Marie: That makes sense. It's a lot about educating and raising awareness about the materials you use. Now, you mentioned the challenges of the past couple of years with the absence of trade shows. How have you adapted your marketing and outreach strategies during this time?

David: Well, in the absence of traditional trade shows, we've had to shift our focus to online platforms. Social media has become a crucial tool for us to showcase our buttons, share the stories, and engage with a wider audience. It's been an adjustment, but we're learning to leverage the digital space to communicate our brand values and connect with customers who share similar interests in sustainable and unique materials.

Marie: That's a smart adaptation. It's fascinating how technology enables businesses to reach a global audience, even in niche markets. In that sense then, looking at the kind of businesses that you work with, they are quite small, artisan type brands, yes?

David: Yeah, that is quite fair to say. We love working with the smaller, emerging brands, and some of them are more established. Our business model is very different. We cannot compete on price; it's just impossible. Some people are selling buttons almost for less money than we can buy the raw materials. It's crazy. So we have to use four unique selling propositions: natural materials, heritage, designs, traditional techniques, and made in England. Fortunately, I think we came at the right time. We were very big proponents of Corozo, which has become a significant button-making material as well. So, we seem to be in the right place at the right time. Here we are six years later.

Marie: Amazing. Well, one of the other things that I wanted to question is arguments around veganism. You've mentioned that there's rennet in the buttons as well, so they wouldn't be classed as vegetarian friendly. Do you see that being a problem for you in the future in terms of supply chain, particularly as people are switching to more vegan and vegetarian lifestyles?

David: Well, certainly, there is a massive interest now in traceability and sustainability. All of those kinds of things are really important in certain parts of the fashion market. They are the number one determinant of what to use; It takes precedence over price. It takes precedence over so many other things. Corozo and Codelite perform differently. And so there are certain applications you would want from a each material. These (Codelite) are much harder. They're much more stable. Corozo is much more porous; it still has a structure to it. So, they do perform differently. So, anybody who's looking for a true vegan product will go to the Corozo, providing it meets all the other criteria that they're looking to tick. If they are looking at a petrochemical material and saying, well, I need to replace the properties of polyester, Corozo won't do it, but casein will. It might not be the Corozo in terms of the vegan part of it, but it's certainly a much, much better material ultimately than a petrochemical. So there is demand for both. I think it is incumbent upon us really to promote the qualities of casein and Codelite.

I would say actually two things (regarding tracability). One thing is the idea of actually restoring production of casein in this country, and there's some really interesting things that you can do with it. And the second is formaldehyde, which acts as a crosslinker. And it's the crosslinking properties that make it hard. But we have identified a similar crosslinker in horseradish root. So, if you can literally get rid of formaldehyde out of the process, it would be a very, very interesting idea.

But we just lack the funding. We just don't have money to do that. And this is a problem, I think, in a lot of parts of the world. You know, if I say to you, I want to build a rocket to go to Pluto, I'll be showered with billions to do that. You know, if I say that I'm trying to restore milk casein production from 50 years ago, it's never heard of; it's a waste of time; there's no money. And that's what we're up against. But what we also then started looking at,

which is really fascinating, is that you can then start to buy organic milk. You can actually buy your organic milk from, as we had a relationship with Yeo Valley. You could buy biodynamic organic milk from Laverstoke, and literally you can go to the farm, get milk, and deliver buttons back on that basis. So the traceability is almost down to a farm on a particular day and a particular herd of cattle. And so when you are in control of the means of production, all that we do is suddenly enhanced, magnified manifold. Yeah. So we're very close, we live very close to Daylesford (Bamford). And you know, this is something that we would love to do. It's actually to say you've got all these cattle grazing on your land. You have your own fashion labels. Why don't we make buttons out of your milk?

Marie: That is the dream, isn't it really? It's exactly that kind of really localized circular systems that we've been looking at from the fiber manufacturing side of things.

But like you say, funding, it's just not a particularly glamorous area that people want to invest in and unfortunately there's a lot more awareness, I suppose, around recyclable materials and that kind of side of things, rather than biodegradables and compostables.

David: Which is the dream. But, but it does go on and you know, we are learning the lessons of global sourcing, which is changing. You can't rely on, say for instance, our material uses Irish milk that goes to Italy, which is then processed. And then delivered here. You know, that as a process is heavy on carbon footprint in terms of moving everything around. It's heavy on time. And having a more local production would drastically reduce and improve the whole economic framework of that, whether it's ecological or financial, but it's just getting that presented in a form that investors or funders would be prepared to support.

Marie: Absolutely. Well, that's fascinating. Thank you very much for sharing that with me.

David: Fantastic. Marie, it's been a pleasure. Thank you very much indeed.

10.1.3 Professor Kate Goldsworthy

The third interview was conducted between myself, Hannah Auerbach George and Professor Kate Goldsworthy on the 26th May, 2022. Known for her work on speedcycles with the Mistra Future Fashion Project and her role in the BFTT, this interview with Professor Goldsworthy aimed to disseminate the theoretical and practical work related to speedcycles and the future vision as discussed in Chapter 4.

Marie: What I'd like to do is just have a discussion about both the work that's been done for WP6 in relation to regenerated protein fibres and fast fashion, but within the context of Mistra Future Fashion Program (MFFP) and the concept of speed cycles.

We're getting to the end of the project and want to evaluate the outcomes so far – and as you saw on Monday – we have faced a few challenges in terms of material development, either through COVID and loss of time or lack of facilities and so material testing isn't at a place where we would like it be but were also starting to wonder what other technical challenges we might face down the line or what difficulties there would be getting this kind of disposable product to market.

This is where conversations around the paper dresses are quite interesting– Hannah conducted an interview with one of the founding members of DISPO a few months ago, and that gave us some great insight into their motivations for making these dresses in the first place.

Kate: I don't know where to start, so I'll just dive in, and then we'll see where we get to. The purpose of the MFFP, it was built on, as you've mentioned, that speedcycle work, trying to handle sustainability strategies that don't rely solely on making things more durable because, you know, in the full fashion landscape, it seemed to us that it really wasn't feasible or fair on a big portion of society. Obviously, at the time, we were working with both H&M and Philippa K, Swedish brands at very different ends of the market. So it felt like a really interesting thing to look at, not just fast and slow, but a spectrum of everything in between. The bit I was most involved in with my own research was the fast end. I also did a mid-speed polyester version because the idea was that it could be as durable as standard garments, but by developing nonwoven materials, you could make something lighter and recyclable. We looked at a full range of end-of-life scenarios.

What's interesting about what you're doing is it's another material group that might be appropriate for the faster end of the market. I think casein, along with many other new biobased materials, doesn't quite stand up to something like polyester in terms of durability, performance, and heat. So, if you think about it, we were working with cellulose, pure and regenerated, and I was working with polyester. This is another group that I think is really relevant. One of the first things we did was look a lot at end of life. We did look at composability and recyclability. With cellulose materials, recyclability was essentially paper slushing, slushing paper, and that was quite successful in terms of what we could do. Compostability was also interesting. We found ways of making it more compostable, making it stronger and more tactile at the same time. But I would say the biggest challenge with compatibility is infrastructure, which at the moment isn't there.

Marie: Yeah, I agree.

Kate: So environmental scientists often think about composability as being very linear. I think there's an argument to that. Industrial composting does produce something useful. If something is truly compostable, that's great. If it's biodegradable, we kind of came to the conclusion that what is that biodegradability serving? If it's not becoming soil, then what?

Marie: I think this is one of the things we found with ours. There's a very fine line between what's actually going to be beneficial for products or material at the end of its life and what is just a bit of a potential short-term solution but doesn't really solve anything long-term. Infrastructure is the big challenge that we're thinking about; we have this nice ideal circular framework where the waste material is going back into the field with the cows. Logistically, the reality of collecting those garments or collecting waste from textile factories and getting it back to the same location and having this really localized system is very far in the future.

Kate: It is. But I think, in a way, you've got to almost bite off what you can do in this project to progress the area. I see this whole field developing a big consortium bid at the end of this that looks at different material types, finishes, and different end-of-life scenarios. The great thing about Mistra was that we had environmental scientists looking at the material in terms of recyclability and compostability. We had manufacturing experts looking at producibility. Consumer studies, a range of light perception studies looking at how the materials might be accepted. We had a team looking at all these different aspects, and that's an enormous job.

Marie: Absolutely. The papers that have come out of that are incredibly detailed. Unfortunately for us there just hasn't been time to get a real assessment of what's coming out of the lab and some elements have had to be more theoretical. We are hoping that we'll be able to take the project further afterwards.

Kate: Don't forget, though, MFFP happened over 8 years. It wasn't all focused on the paper, but what we did in the second half was amazing. It was essentially two 4-year projects. If you think about BFTT, we're all getting to know each other and particular areas of work. Then, in the second four years, we found connections and did things together.

Marie: Yes.

Kate: We had all those different disciplines focused on the paper because, as a consortium, we decided it would be the focus for everyone. Then, we built everything else around it. That doesn't happen very often in research projects. You don't get years. But I do think it's almost given a bit of a blueprint in my mind of what needs to happen to push it forward. I think with amazing connections with people like Leeds and Loughborough, I'm talking beyond; there could be so much. Your additional work, like the historical perspective Hannah's doing, I think is really important. That was definitely a gap in what we did. We did a kind of practice review, and Kay Polytonic did an interesting study on paper clothing.

Marie: Yeah. When I was first starting out and coming across all this research, honestly, I found it quite confusing to know what part of what project everything was. But there's definitely a short paper that I found somewhere online around different types of natural dyeing on the papers as well.

Kate: Oh, that, yeah, no, that was the practical embodiment we did as part of it. Another strand was a two-year engagement with Philip K where they explored what it would mean for them as a label. They ended up with one of the garments in the V&A as a collected item, but it's the eternal trench coat, the polyester one. Just one they made out of a nonwoven Tencel in the end because they wanted it to be a commercially available material, and the paper was not really commercially viable at that point. It was still a lab product. But Kay also did a big study of, for example, in the 1920s or something, there was someone wearing paper.

Hannah: There were lots of paper collars and things like that, or like garment and accessories features. So, you would change your collar more often.

Kate: Exactly. She did that research, which probably would cross over with the work you're doing.

Hannah: I would love to see it.

Kate: I think it's the beginning of a conversation. The reality is I don't think they will make their garment out of the material we explored in Mistra. I think they'll be looking at commercially available, but I would love to think about how we could bring these things together and present to them some more future-facing ideas as well. Just keeping in mind, this is a hot topic and it's super interesting. I think you guys are really filling a particular gap, especially with the potential for protein and casein. It has this amazing, rounded historical background. I'm super excited about it. I don't know quite how to bring it all together, but I think it makes sense that this is a UAL-wide piece of research.

Marie: Absolutely. I'm trying to figure out how to bring everything together for my own thesis. There are so many different sides to it with the historical, design, materials, mono-materiality, and the regenerative framework. Tying in all this incredible historical research around the political and social significance of RPFs during the war. There are nice parallels everywhere, and it creates a really lovely narrative. I'd love to write proposals for each area on how they can be taken forward, proposed to industry, or become part of a new research project. Conversations with brands like Philippa Kay show how something can move from research to industry, which is incredibly exciting.

Kate: Even Philippa K; they didn't want to talk about fast at the start of this project. They were like, we don't have any fast products. Then, when we did this embedded program with them, we literally worked with a group selected from around the company, from people on the shop floor to those in materials, marketing, sustainability department, supply chain, and everyone. When we started with an analysis, we said, OK, what's your fastest product? Going through that process, they realized they had pop items, a color each season designed to pull people in. It's like a signifier of something new in the shop. It was a one-season product, their fast product, not likely to sell out completely. From there, it opened up a different conversation with them. They redesigned the paper clothing we were working on in the research. The prototyping was looking at very fast wear, not disposability but utilitarian garments. They wanted to look at fast like a glass of champagne, a very luxurious thing worn maybe two or three times. They twisted the strategy to suit the story around the garment. It was really interesting.

Marie: Yeah. Thinking about things in that way is something that's come out of the project for us. In the initial material development and learning about casein properties, we can see within fast fashion there's a broad spectrum of uses. I've been working on quick-to-make T-shirts, going-out garments, or items worn once and thrown away. But I've also developed samples for a regenerative disposable garment that's compostable and mono-material but might last a couple of seasons. Understanding how we look after garments and what we want from them is interesting in the conversation around fast fashion, as it's not all bad. People often associate disposable or fast fashion with negativity, like a dirty word.

Kate: Another commercial project you're making me think of. One of the big brands is looking off the back of

Mistra, looking at garment archetypes. The environmental impact department focuses on what you're replacing. They have a baseline garment to understand impacts and compare new developments. You need a different sustainability approach with a formal jacket than with underwear or a party dress. One big High Street brand is doing an in-depth look at garment archetypes and use patterns. There's no research that really does that, and it's a massive gap. Brands have data on what people buy and when. It's interesting and something you might consider in your PhD.

Marie: Yes, there's a huge gap in that area. Trying to find research on the environmental impacts of specific garment types is difficult. The breakdown of items is lacking, and it's a challenge to find statistics beyond general statements about clothing disposal.

Kate: Absolutely, it is. It doesn't exist. This work could keep you busy for the next 20 years. Make sure you know the output and dissemination because the most useful thing about Mistra was being able to publish from it. Once you've done that, others can access it, and you can build further work. I'm thinking about how to make sense of clusters of future work. It's a nice way to work. Infrastructure and feedstock are also crucial, and there's lots of work going on. A cross-comparison with the Mistra LCA work could be interesting in your case, even with lab-based materials, to provide a way to explain the benefits.

Marie: Absolutely. Bringing it back to the overarching vision we sent over, any general opinions or disagreements? I'd appreciate your perspective and comments.

Kate: I'd love to go through it in more detail and add some points. I haven't noticed anything that jumped out at me on my quick read, but let me delve into it more thoroughly with that perspective. I'll provide comments in the document itself.

Marie: That would be fantastic. I appreciate it.

Kate: I'll add some comments in the actual document regarding the garment and overall vision.

Marie: That would be amazing. We're really looking at the barriers from a legislative and policy perspective to moving into compostable items. We've seen how recycling has been taken up quite well with brands and local councils collecting items for recycling and encouraging consumers to reuse/recycle, but getting to a similar level for compostable items is challenging. Defining compostable items in the textile general sense is complex.

Kate: Do you know Laura Solomon, the R&D fellow? We worked on a project with Ananas Anam, a year-long project on challenges and opportunities around biobased end-of-life options.

Marie: One final question. One of the main barriers to sustainability, even in a circular economy, is overproduction and consumption. How can designers ensure materials and systems are used responsibly by brands and consumers? How can we bridge that gap?

Kate: I think there's too much pressure on consumers. Expecting them to understand the complexity and act on it is too much, especially for those just trying to survive. It can feel insulting. I don't think all cheap, fast-fashion garments are bad. I have a durable, cheap H&M top that lasted for 15 years. Young people, influenced by social media, wear something once and send it back. It's a culture issue.

Marie: I agree. People's actions and opinions can be contradictory. The subconscious pressure from social media makes it hard to change habits.

Kate: I think sometimes we try to cram too much into one box. In this project, if you can show a space for beautiful, useful materials and garments with a shorter life frame, that's positive. You can't guarantee how garments will be used, but you can suggest it.

Marie: It's a huge topic, and more diverse research projects are needed because there's no one-stop solution. Clothing is personal and has cultural, financial, and economic requirements. We need multiple scenarios to adapt to the changing world.

Hannah: People often have questions about the ethics of fast fashion, and it's important to emphasize that there's no one solution. This material is one cog in a huge machine.

Marie: There can be an issue with people doing this research and making broad generalizations.

Kate: It really is.

Hannah: White women like us, from a fashion background, have an innate understanding of materials, and that's why we're interested in researching them. But we are also the demographic that can afford more durable, high-end, expensive, handmade items. There's an element of that influencing the angle for the past 20 years. The cost of living crisis is making brands reassess, and having a globalized view is crucial.

Kate: Reminds me of the British Council project, "New Landscapes." We did "Denim to Denim," discussing sustainability and circularity with stakeholders from Nigeria. Hearing perspectives from those experiencing impacts but not involved in creation was enlightening. It's challenging to see that from a privileged point of view.

Hannah: There was a discussion about clothes donated to Third World countries and their appalling condition. People donate worn-out, stained clothes, expecting gratitude. Places are refusing donations now due to overwhelming amounts.

Kate: Dealing with our waste will become a challenge, even for companies doing good stuff. Logistics barriers and legislative differences globally affect waste management. Your project's potential to deal with local waste streams is valuable.

Kate: Think dealing with our own waste is going to become big, you know, because actually even the companies that are doing really good stuff, with recycling, there are massive logistic barriers with getting waste from across borders because certain countries won't permit things either in or out. And textiles are very heavily legislated and legislated differently in different parts of the world. So, another really good thing about your project is you potentially deal with local waste streams.

Hannah: And that's a historical thing as well. There is a load of stuff about the shoddy industry and tariffs between Europe and the UK. Germany was penalized for importing fabrics that had too much fake silk and rayon in them and trying to pass them off the shoddy to pay a lower tariff or something. I can't remember exactly which way around it was there. It all comes around, though. It's ongoing.

Marie: I'm cautious of time, and if you have to run, the final thing is to go over the vision and work package 6 project report. Perhaps we can continue with the conversation another time?

Kate: Yes. Best of luck. Looking forward to it. Have a good day.

Hannah: Bye.

Kate: Take care. Bye-bye.

10.2 Consumer Survey Results

This section documents the full results of the consumer survey, first discussed in Chapter 4.

Q1 How old are you?			
Answer Choice		Response Percent	Response Total
1	16-25	7.5%	9
2	26-35	50.0%	60
3	36-45	26.7%	32
4	46-55	9.2%	11
5	56-65	5.8%	7
6	66 +	0.8%	1
answered			120

Appendix Table 1: Consumer Survey Results Question 1.

Q2 Which of the following categories best describes your employment status?			
Answer Choice		Response Percent	Response Total
1	Employed, working full-time	68.3%	82
2	Employed, working part-time	11.7%	14
3	Self Employed	6.7%	8
4	Not employed	2.5%	3
5	Student	8.3%	10
6	Retired	2.5%	3
7	Disabled, not able to work	0.0%	0
answered			120

Appendix Table 2: Consumer Survey Results Question 2.

Q3. On average, how many items of clothing do you buy in one month?			
Answer Choice		Response Percent	Response Total
1	1 or less	56.7%	68
2	2-4	37.5%	45
3	5-7	5.0%	6
4	8-10	0.8%	1
5	10+ (please specify):	0.0%	0
answered			120

Appendix Table 3: Consumer Survey Results Question 3.

Q4. What is your main motivation for buying new clothing?			
Answer Choice		Response Percent	Response Total
1	Seen on social media/online advertising	13.3%	16
2	Worn by celebrity or influencer	2.5%	3
3	For a specific occasion (holiday/night out/wedding etc)	45.0%	54
4	Replacing of worn-out garments	46.7%	56
5	None of the above. I buy clothing when I need to	22.5%	27
6	Other (please specify):	19.2%	23
answered			120

Appendix Table 4: Consumer Survey Results Question 4.

Q4. Other (please specify):

- Finding a garment I want
- Driven by the design itself, I teach fashion so I am quite aware of the labels around
- When there's a sale on
- Compulsive need to spend
- Love to change up my wardrobe
- for growing infant
- I tend to buy clothing because I browse online and see things I like.
- I don't think is's possible to specify a single motivating factor: I buy clothes for a mixture of practical, aesthetic, identity and status reasons; and to replace worn out clothing or garments that no longer fit.
- Impulse buying
- Sales
- When I need an item or would like to something new/exciting to wear (or need a pick-me-up!) but I only shop second-hand or local!
- gender transition and reconstituting wardrobe
- Just some new work clothes sometimes
- I just like to buy clothing
- Personal style development and expression
- Sales
- If I see something I particularly like
- I haven't bought any clothing this year and don't plan on it for the rest. It was as a goal set in January 2022.
- When I see something I like
- the buzz of having something new.
- Negative mental health behaviors, "self medicating"
- Refreshing my wardrobe
- And just adding to my wardrobe but I look at the same websites rather than respond to ads on social media.

Q5. What is your main motivation for discarding clothing?			
Answer Choice		Response Percent	Response Total
1	No longer in style/bored of item	23.3%	28
2	To make room for new clothing	23.3%	28
3	No longer fits	44.2%	53
4	Poor quality or broken (such as a tear, stitching come undone, pilling, loss of colour etc)	55.0%	66
5	Other (please specify):	10.8%	13
answered			120

Appendix Table 5: Consumer Survey Results Question 5.

Q5. Other (please specify):

- I do not discard clothing, I just expand wardrobe. I still own clothes I had while in higschool
- worn out
- Worn out holing etc
- I discard clothing that no longer meets my needs, because it was a poor buy in the first place, or be cause it is worn out or no longer fits.
- Cannot be passed on to someone else, cannot be repaired or used for something else
- eaten by moth
- No longer suits
- I no longer wear the item for a variety of reasons
- When I say "no longer in style" I mean doesn't feel like "me" anymore (feels immature)
- No longer associate with my personal identity
- Don't wear, doesn't fit right
- Once it's worn out/has holes in it.
- Plus sized body = more friction = pants die faster

Q6. How are you most likely to discard your clothing?			
Answer Choice		Response Percent	Response Total
1	I use textile recycling bins	16.7%	20
2	I donate to charity	65.8%	79
3	I upcycle my garments	0.8%	1
4	With my general household waste	3.3%	4
5	Other (please specify):	13.3%	16
answered			120

Appendix Table 6: Consumer Survey Results Question 6.

Q6. Other (please specify):

- H&M garment recycle scheme
- Vinted selling
- Sell online
- I transform them myself. Let's call it upcycling
- Sell on vinted/eBay
- Use in rags; if cannot find use, tend to hold on to clothes without clear place for it to go.
- Share with friends then charity
- I also recycle using textile recycling bins, and I give away clothes to friends too.
- I give them to friends
- A combination of charity donations, textile recycling bins and offering it to friends
- Sell
- I give to friends/family
- sell
- I either donate it to Charity or use textile recycling bins. If it is still wearable but I no longer want it, I will sell it on Ebay or Vinted.
- Do my best to repair until repair is no longer possible and garment is not useable
- Sell on vinted or take to charity shops

Q7. What do you most associate with high 'quality' clothing? (Order of importance from 1-5)			
Answer Choice		Total Score	Overall Rank
1	Well made	493	1
2	Durable materials	432	2
3	Fit for purpose	375	3
4	Expensive	263	4
5	On trend	237	5
answered			120

Appendix Table 7: Consumer Survey Results Question 7.

Q8. Do you associate high quality clothing with sustainability?			
Answer Choice		Response Percent	Response Total
1	Yes	38.3%	46
2	No	9.2%	11
3	Sometimes	52.5%	63
Please explain why:			96
answered			120

Appendix Table 8: Consumer Survey Results Question 8..

Q8. Please explain why:

- In current climate I would assume companies involved in high end fashion would have an eye on sus tainability
- I mean… some high quality clothing isn't sustainable at all. Just like anything in the wider beauty industry. Not a lot of companies ACTUALLY care and act on sustainable options. Even when they say they do!
- As it lasts longer and won't need replacing
- It's not always something that enters my head, guilty of a "they'll do" attitude when I need to go clothes shopping which I avoid as much as possible
- The price tag on some company's garments are higher due to the cost of materials/labour with the un derstanding that they are sustainable/promoting fair pay for workers , however, more expensive materi als can also be less eco-friendly and not sustainable!
- I expect producers of high quality clothing to consider sustainability issues more than I would expect fast fashion brands to
- I tend to find higher quality clothing is better made and therefore lasts longer. If I'm buying second hand I choose higher quality brands.
- Maybe not in terms of manufacturing but high quality lasts longer, is generally more durable and is usually more expensive so not as 'disposable'
- Because the high quality means better production and possibly better materials and fair payment of the workers involved throughout
- Durability, prolong lifetime
- High quality means it is built to last
- It just seems like a low level of sustainability because of the seasonal nature of fashion.
- Because sometimes I buy from people who make clothes from old/recycled fabrics
- Depends on the materials.
- Fast fashion I associate with cheap clothing and this I know isn't sustainable
- Better quality = long term wear
- Construction is key quality. Sustainable fabric and production don't guarantee quality
- I know marketing can be deceiving and have also bought expensive clothing which hasn't lasted long
- I don't know much about sustainability to be honest! I would think high quality means it would last a long time though and less likely to be thrown away/ more likely to be worn for a long period of time.
- I believe better quality clothing lasts longer and as such I buy less
- It depends on the brand, although I tend to view any brand claiming sustainability with suspicion these days.
- Better quality means it will last longer/ I can get more use out of it.
- I try to preserve items i buy that have cost a lot of money on and find they do last longer
- High quality clothing should be an investment, last for many years.
- High quality in my opinion is the use of 'good' use of resources, but it lacks the equity and justice ele- ment.
- High quality is subjective, sustainability is not always a value I see linked to quality clothing.
- I'd expect seaming, material selection and construction to allow the garment to have a long life span. I do not purchase expensive clothing that looks shoddily made or is trend driven.
- An expensive brand doesn't mean its been made sustainably.
- Sustainability means it will last longer and therefore constructed better
- I know that not all high quality items are sustainably made, but i'd hope they'd last longer, or be more of a classic piece so i wouldn't want to replace them quickly

- I think quality makes me think there's good connotations around the way it was made. But appreciate when reflecting on whether it means sustainability, I realise it's not.
- I'm unsure what quality testing is done on sustainable clothing or items from smaller businesses. Gener ally larger suppliers have more money to "test" items for wear.
- I would expect brands who make high quality clothing to have considered sustainability as part of their ethos. To me sustainability is part of what makes it high quality.
- They are not necessarily sustainably made but they are likely to last longer, therefore negating the need to replace them
- Only if the materials are sustainably sourced. Fast fashion chains like ASOS do have upmarket quality ranges, but they're still made by ASOS…
- I would feel they were more sustainable as they would last longer/get more wear and therefore would be less of a waste.
- I wish there was a correlation, but sadly there's other factors at play. It can be sustainable in the sense that you will wear it for longer (and therefore you don't need to buy more), but if the material is going to last for hundreds of years in a landfill, does it matter if it lasted 2 or 10 or 20 years in use?
- If it won't instantly get thrown away or damaged then more likely to last better but it being an expensive brand doesn't mean their practices are sustainable
- Sustainability is important to me and for me, an item of clothing isn't high quality unless it has been produced sustainably.
- High quality / long life garments will replace the need to buy new ones and reduce the impact associ ated with consumption
- A lot of it depends on how I would look and feel when I wear any clothing so the silhouette and mate rials are very important parts of a garment; how the greement is made/designed and how the materials are sourced are crucial in quality clothing.
- well the word sustainability is slapped on everything these days, so unless the company is known to me as being sustainable I sometimes believe it. But with the entropy of the universe, nothing is really sustainable
- In my opinion If something is of high quality, it's made well in terms of sewing construction, durable fabrics, good hand feel etc, and this is irrespective of the sustainability of the materials used to make it. The only exception to that I guess is that if something is high quality, it will last longer, and that's tech nically more sustainable than something that breaks after one wear. It's slow fashion.
- High quality usually means it last longer, and is classic in its styling rather than fast fashion/trendy. If I don't need to throw it out and replace it, then surely that is more sustainable - almost irrespective of what material it is made of? I'm very much a subscriber to the Vimes' Boots Theory of Economics (see Terry Pratchett or Jack Munroe/Bootstrap Cook)
- Clothing that lasts longer and that you wear for longer is more sustainable - and my most wasteful purchases have, ironically, often been motivated by saving money (but have ended up being things that I rarely wear); or saving time (panicked last minute purchases). So high quality clothing can be more sus tainable in that sense, but one never knows exactly how a garment has been produced and how the constituent textiles have been made. The word 'durable' makes me think of scratchy wool - I often prefer softer fabrications, but I do want my garments to last. I'm not sure if I would use the word durable though - it doesn't sound very sexy or fun.
- I expect high quality clothing to last a long time.
- If you are paying more the companies have a duty to use their higher profits to be more ethical
- A high quality garment should last and be fit for purpose. Sustainability can mean different things. A sustainable garment made of hemp but is not constructed too last is not a high quality garment

- Higher quality clothing may last longer so fewer replacements would need to be bought. It also sug gests better pay for supply chain workers (but that isn't necessarily true).
- raw materials have been chosen according to their sustainability production process is link to sustaina ble choices.
- Quality means it lasts longer, which means I have to buy less, so that should be more sustainable.
- "If you buy high quality, it will serve you longer, you will be more satisfied and you have to buy less. Buy ing less is the single most important thing we could all do for sustainability, but of course, nobody is saying that. If the item is completely biodegradable, it is slightly different, but we should not forget that it still has to be manufactured and transported to us.
- I think responsible and sustainable manufacture is correlated to high quality
- Sustainability is a very complex issue and I fo not thinkl that just wearing beige cotton is the answer.
- A high quality garment can be produced with completely non-sustainable methods. However, it is more sustainable assuming that it lasts longer.
- I believe better quality clothing lasts longer - less likely to wear out, become misshapen with wear - and so will be worn for longer and not need to be replaced.
- High quality lasts longer. You enjoy wearing the garments for longer
- Brands often cut corners with recycled materials
- It is usually more expensive
- I think I over associate the terms " high quality clothing " with luxury brands which feel the most frivolous
- If a product is well-made/durable with functionality in mind, it will last and stay in circularity (not buying NEW clothes / being able to wear and wear your clothes is sustainable)
- Insofar as I think of high quality clothing lasting longer.
- I associate sustainable clothes with previously owned items, up cycled clothing
- I guess I think if high quality clothing tells me it's sustainable, I'll believe it. But some lovely things use harsh dyes and bad labour practices.
- Not all high quality clothes are made using sustainable materials
- A garment must be made to last (great material and well made) and be versatile enough to be worn frequently and in different contexts. A long and happy life = sustainable.
- If it can last a long time, and also in it's taste and construction be "timeless" I see it as more sustainable than clothing that pills/tears/fades quickly. Also if it's too trend specific it won't be worn that much.
- Usually the materials used by sustainable brands are better quality (no polyester) and made to last. I don't associate high quality clothing with price. I've had expensive pieces fall apart way too quickly.
- High quality should last longer and be worn often, thereby reducing need to throw away.
- Not always, I think 'high quality' garments are not few and far between, especially in the world of high fashion and couture. However, these garments are not always sustainable. This is not to say that high quality garments can't be sustainable though. When I think of high quality clothing that is sustaina ble, I think of something like a bespoke suit or a bespoke pair of shoes. The entire process can be sus tainable and is possibly one of the most sustainable garment manufacturing methods in practice. Firstly, it's a financial investment, which I think encourages the wearer to look after it and increase its longev ity by taking it to be repaired and altered where needed. The garments that are coming out of Savile Row for example tend not to be following current trends. The fact that it is often not 'hot off the catwalk' in style also increases its longevity as a garment or accessory, because it almost doesn't have a life span dictated by fashion trends. It is also handmade by a craftsperson, who is likely paid a fair wage. You also have the ability to select which materials you would like your garment or accessory made from and as part of the service, you are invited to view the process from start to finish. By offering this, I may be wrong, but I think it anchors some workers rights and ensures transparancy from the bespoke trade to ensure that their workshops remain places of interest and pools of talent rather than sorry sweatshops. So overall, when I think of high quality and sustainable, I'm thinking of clothing which al lows you to 1) invest in talent and secure fair wages for craftspeople by charging a price that reflects the quality, process and labour and home grown industry, 2) encourages you to slow down you consump tion by offering you a high-quality, timeless and re-workable product and the choice to select materials that you would like to use instead of forcing potentially green-washed and unethical options on to you.
- Because if it has high quality it will last longer thus it is more sustainable
- the term sustainability is relatively new, I associate high quality more with durability.
- If a garment lasts longer due to its build quality and, importantly, timeless style then this may be more sustainable than purchasing and disposing of multiple equivalent garments in the long run. However I would suspect that a large majority of high quality clothing is being purchased by consumers who already process a more than adequate wardrobe and is therefore creating additional negative envi ronmental effects. E.g. if someone already possess 10 high quality coats then the net environmental effect of adding an 11th high quality coat would be negative. But if someone owns 1 high quality coat for many years as an alternative to purchasing, using and disposing of 5 low quality coats during that equiv alent time period the net environmental effect would be positive.
- Many expensive brands aren't sustainable at all
- Because if something is made well, it will last longer and so will not need replacing as often.
- In an ideal world, yes.
- The highest quality clothing I own often encorporates synthetic fibers which are usually necessary for comfortable and appropriate fit on a plus sized body. I also associate consumer cost with sustainability and my willingness to actually wear an item and get USE out of it because if it was expensive the urge is to treat it with kid gloves and then the solution is to fill the gaps with something less expensive anyway.
- If I buy something that is high quality, then I expect it to last, which is more sustainable than buying lots of cheap, poor quality clothing. I would add that high quality clothing is not always the most expensive. For me I look for the quality of the fabrics, quality of the garment construction, and sustainable fabrics.
- Primark is the opposite of high quality and that's dog shit and made in Bangladesh
- Depends on the brand.
- High quality clothing is generally not discarded because it is more expensive, well-made and designed therefore ensuring a longer personal attachment with the consumer.
- Yes if the quality of production is high, however a lot relies on the material. Use of polyester etc. Lowers the sustainability of the item.
- I would like to believe this but sadly not all expensive clothing is made from sustainable materials - I guess you could say if you pay more then you might keep it for longer?
- Some brands are ethical/sustainable, some aren't, regardless of price point.
- Clothes should be made to last but also make you feel good in them, better materials and well made clothes fit better and therefore kept for longer periods of time or still good quality to be sold 2nd hand.
- A general perception that very cheap brands (e.g. Primark) have a reputation for poor build quality. That being said, I don't assume that some very expensive brands (e.g. Balenciaga) are of an especially 'supe rior' quality toamy more high street brands
- It is less likely to wear out
- Some 'high qual' brands are not as sustainable as one my think.
- I would like to make this association all the time but appreciate it is not always the case. When I re search a brand I am considering buying from, I often find that some high quality clothing companies have a focus on sustainability. However I do not think that high quality equates to sustainability.
- I will wear it again and again for years and ensure I get plenty of use out of it. I like to buy classic items

that won't go out of style and get annoyed when they're not durable enough to last the test of time.

- Brands like Patagonia I think of as high quality and sustainable as it is a key part of their messaging. However something like white company is high quality but I don't think it is necessarily sustainable.
- Quality usually means it will last longer and be more sustainable
- Lasts longer so I'd need fewer clothes over my lifetime
- Good quality material is not necessarily made from sustainable sources.
- I'd like to think more expensive clothes meant better quality. This isn't always the case.
- Not all high quality clothing is sustainable, and there needs to be an awareness of a certain degree of greenwashing.

Q9 How important is durability when choosing an item of clothing?			
Answer Choice		Response Percent	Response Total
1	Very important – I prioritise this over style or cost	17.5%	21
2	Moderately – I choose durable items where I can but sometimes, I can't afford them	60.8%	73
3	Slightly – I prefer for items to be durable but do not priorities this over style	21.7%	26
4	Not at all – Durability is not a priority for me	0.0%	0
Comments (optional)			21
answered			120

Appendix Table 9: Consumer Survey Results Question 9.

Q9. Comments (optional)

- It would be very very important if it wasn't for cost
- It really depends on the purpose of the garment
- I would love to buy high quality durable items. But the high price point doesn't always make it possible.
- It depends on why I am buying the clothes
- Durability matters in specific contexts. For camping gear, durability matters. For everyday clothing, durability is less important. The one piece of clothing which frequently fails me (because of durability) are jeans I cycle in - everything else dies other clothing deaths.
- It depends on the item. A coat I would want to be durable. A summer strappy top I'm not so bothered about and if it breaks I'd fix it anyway with a needle and thread. I'd
- I get really cross when things do rip, tear or fray after one or two washes/wears, and try to avoid that brand again. Shopping for clothes is not a fun thing. It is a thing I have to do, so the longer something lasts the better. I have pairs of jeans that are now almost more patch than original jean. I have fleeces that have gone from being smart to being gardening wear. I tried being stylish once - it was very expen sive.
- I want my clothes to last, and I wash and care for them, but I don't want to wear ugly or unappealing fabrics.
- When I buy for my children, I ask myself if the garments will be in a good state to be passed to other children in the family
- I wear things into the ground as I dislike shopping, but I will wear less durable things even when they get holes/fray/bleach
- I'd say my answer would truly lie between very important and moderately.
- Durability is not an issue in the UK, customers got used to good quality items for a low price anyway.
- I buy the majority of my clothes second-hand so they aren't always durable but I'm giving them a sec ond life.
- "I don't think the above option accurately describes my thinking -- but I will almost never buy something that seems to me like it won't last a long time.
- For me transactional utility is key. Is the high quality garment good value, this will often sway me one way or another.
- As a plus size person, I often have to take what I can get, not what I would want to buy.
- I WANT a higher quality, sustainable, durable wardrobe. Only option is to wait for sales where the price reductions are usually a joke and popular sizes are gone within minutes or at least well before the end of the sale.
- I won't buy something if I think it won't wash well, loose it's shape or wear easily. I choose clothing which I know will last well, both in terms of fabric durability, as well as trend durability. I try to buy classic piec es which I know I will still love wearing in years to come.
- I invest in shoes to make sure they last, however I often do struggle to afford durable items. I tend to buy clothing from charity shops but make sure I check the quality / materials before purchase.
- I buy expensive clothes because I wear them for years and years and feel I can therefore justify it. I do not buy fast fashion. Not opposed to it but I have found a few labels, that tend to be expensive, to be very durable.
- I can't afford to prioritise durability over cost and it is no use it something is durable but unwearbly ugly or out of fashion.

Q10. How does the term 'Disposable' make you feel?			
Answer Choice		Response Percent	Response Total
1	Angry	25.8%	31
2	Uncomfortable	45.8%	55
3	Unsure/I don't feel strongly either way	22.5%	27
4	Positive	0.8%	1
5	Other (please specify):	5.0%	6
Please explain why:			80
answered			120

Appendix Table 10: Consumer Survey Results Question 10.

Q10. Other (please specify):

- complex.
- Uncomfortable when it comes down to clothing. In other context it might not be so negative.
- Cautious
- it is part of the market economy we live in, if the governments of the world dont tackle single use items why should I the individual have to deal with negative feelings
- I could easily imagine disposable underwear, as long as it is of natural materials. Other items of clothing,

it's more difficult.
- disappointed

Q10. Please explain why:

- Brings to mind disposable society: high waste and low recyclability
- Fashion is only just being held accountable for its enormous part in the downfall of the environment. It is starting to whisper about it, but it's nowhere near enough, and influencers and the bullshit of social media perpetuate fast fashion and it drives me BONKERS
- "Depends how it is ""disposable"" If it won't clog up a landfill for years I think it can be OK. Some people have conditions where thi gs being disposable can be better"
- I personally feel that clothes should be built to last and make attempts to fix old clothing. Fast fashion and the idea that clothes are "disposable" promotes practice that is harmful to the environment.
- I hate the idea that we throw so much away but recognise I am part of the problem
- It makes me think of sweat shops In poorer countries to feed an unnecessary appetite for fast fashion.
- Because even if is used in fashion no garment can yet be disposable.
- I don't think items should be disposed
- It sounds callous and frivolous considering the state of the world
- The many costs incurred in the fashion industry: human rights abuses, water pollution and wastage, massive increases in air pollution. With all this if the end product if deemed as disposable it's not worth the cost
- As it seems wasteful
- Feels wasteful
- Know it's just going to landfill, not good for the eco system
- Clothes shouldn't be disposable
- I know that throw away fashion is causing major problems from how it's produced to land fill
- I like to think something is used again but sometimes a garment is not fit for purpose so I would dispose of it
- I feel as though it simultaneously one of the major problems AND the major opportunities we face in for the future of sustainability.
- It can be a negative term as it often means throwing something in the bin. However, the true meaning of disposable is that something can be disposed of properly which should be seen as a positive.
- It is synonymous with fast fashion which has negative connotations
- I dislike the idea that clothes are disposable - the impact on the environment for clothes that will be worn just a handful of times is ridiculous. I also have concerns about the ethics of some manufacturers in regards to workers rights.
- Typically associated with items that are not reusable/recyclable. Has negative connotations when con sidering sustainability.
- Unless the garment is in a medical setting where it is one use for safety reasons disposable clothing that is trend based concerns me based on impact to resources.
- Clothing should not be disposable. It should be recycled or passed on when it can be.
- People have no respect for the impact making something and putting it into the qorld has, whether socially or environmentally. As long as fast fashion exists, people will consume it
- it makes me think of items that are made to throw away - things like wet wipes or packaging
- I don't like how many of my items can just end up in landfill! However, I seem to choose more dispos able clothing as it tends to be cheaper.

- We have too much landfill, it's frustrating that items are disposable
- As human beings we've become too used to convenience and single use items. What we're saving in time and effort we are taking from the environment, and long term this is catastrophic. It makes me feel uncomfortable as it involves making adjustments to my lifestyle.
- It just makes me think of piles of clothes in landfill. Clothes aren't disposable! But at the same time I definitely feel uncomfortable about my reliance on ASOS. Unfortunately it's addictive and convenient. It has so much range - so it's easy to express your style.
- I don't like wasting things and this term makes me think of unnecessary waste.
- Disposable for what reason? Paper dresses used to be a thing and they served a purpose - matching lifespan of use to material. Disposable for the sake of disposability isn't a positive attribute though.
- Such a waste
- By nature, something disposable is intended to become waste, and we don't need any more waste! In my opinion, making something disposable demonstrates a lack of respect for the environment, for the purchase cost of that item, and for the resources that have gone into producing something. We can make things that last, why should we make things not intended to?
- Considering an item into which so much work and resources has gone into as throwaway is very prob lematic
- it is part of the market economy we live in, if the governments of the world dont tackle single use items why should I the individual have to deal with negative feelings (p.s. I dont buy dresses but a response was required for question 11, so if I bought one I expect it to last a while lol)
- It's a hard one. If we move towards a circular system where waste textiles can be made into new fibres then we can manage with textile waste and disposable items a little easier. It's not the ideal solution at all, but it would allow fashion to remain (to some extent) 'fast' for some markets and also help man age over consumption and unchanging consumer attitudes. It would also provide an outlet for waste textiles that eventually cannot be worn again through wear, which is inevitable. I think we need to promote 'make do and mend' because things can be sewn back if they break, even fast fashion can be kept in circulation. Clothing can be kept in use phase for longer even if it's cheaply made, if consumers are engaged with sewing and donation activities. But eventually that item of clothing will need to be disposed of. And we need an outlet for that.
- "Disposable tends to mean cheap, un-valued, expected to be thrown away.... and most 'stuff' isn't really that disposable. When we throw it away it becomes someone else's problem - either in terms of landfill, or expending time and energy to dismantle and re-use or recycle. I'm very grateful that there are more textile recycling bins now, but that doesn't mean that I am happy that I end up 'throwing away' clothing that should have lasted longer. And there's something very ""mid dle class white saviour"" about exporting our discarded clothing to other countries..."
- Clothing shouldn't be disposable - it's morally problematic to treat it as such.
- I don't think clothes should be made to be disposable!
- I think you should love clothes and that you should get a lot of wear out of them as not to be wasteful
- I associate it with waste
- It makes me think of landfill and all of the highly processed materials (plastic, fibre, electronics) dumped and going to waste, and the environmental effect of all the energy used to make these things as well as the component waste, all of which are contributing to global warming and shortages of oil and precious metals.
- disposable clothing is clothing that is so inexpensive that consumers feel they can buy, discard and buy again - enabling them to keep up with the latest trends.
- Depends on the context. In terms of clothing it's only "good" in terms of PPE as far as I can think.

- I am very suspicious about sustainability clams. There is so much green washing around. Companies typically stress only one aspect of this complex process, the one that suits them to stress. Disposable items could be good for the environment, or may be worse than the existing ones, it depends on so many factors (what happens with it before it gets to the user, and what happens after). If I could see the evidence that it is better, I would be persuaded to start using disposable clothing (only selected items, obviously).
- Because it is very wasteful, unnecessary and irresponsible
- Garments are not supposed to be disposable, given that you buy them because you like them.
- The state of the world with climate change!
- Things that are disposed should decompose
- Because it doesn't disappear it lands in someone else's hands to deal with. Disposable is misunderstood as though it evaporates. We're allowed to stop thinking of something we owned at a certain point if it's disposable.
- I suppose it depends on the context of the use? I don't like the idea of clothes being disposable, if that's what's being impliedl.
- I understand that during a time when we're battling many pandemics, some things may need to be dis posable. And I also understand that the way people are expected to dress and present themselves (like it's kind of critical to look contemporary when you're job searching) means fast fashion feels necessary for them, I just wish there was a perspective shift. I also get upset at the idea of disposable clothes be cause I think of unsafe factories and awful working conditions. Disposable workers. That makes me very angry.
- I don't have an immediate gut reaction to it on first read. When I let it resonate, I think more of dispos able income or the concept as a whole (a person being disposable in an ableist way - yikes).
- Bad attitude, takes everything for granted, wasteful
- The term reminds me of the entire fashion industry. They make clothing so poorly, advertise the trend, advertise that the trend is now over or "out of style", they make us feel bad wearing it, and then sell us something new. It's really upsetting that we see clothing, made by two hands, disposable.
- In relation to clothing it is a negative and careless term that does not value the resources that have gone into its creation.
- Disposable makes me feel angry, especially in the world of fashion. I feel as though, it is a hugely important term which isn't taken very seriously by consumers. I am very concerned that we are still consuming brands like 'Pretty Little Thing' and 'Boo Hoo' at the rate that we do when we are well aware of the environmental consequences.
- Because it is not only bad for the environment but also means I'm wasting my money on something that is not worth it.
- we could do better.
- It's generally well understood that in any industry disposable items are going to cause all manner of environmental and ethical negative externalities.
- Re-use was the norm for everything when I was growing up. Some disposable items have made my life a lot easier (e.g. sanitary products), but why should clothing be considered disposable? There is no ben- efit to anyone other than shareholders of large organisations.
- There is no "away". We live on a finite planet. Also angry how difficult it can be to make positive choices and decisions.
- It just means it can go in the garbage. There are positives and negatives to that and without context this seems purposeful obfuscation. With the rest of this survey in mind, the first thought I had was re: dis posable income, which is something I have never had and absolutely corresponds to my ability as a plus sized person to clothe myself in quality garments.
- Throwaway fashion is incredibly bad for the environment and society. We should be making fashion that is good quality and which lasts, not fashion which is worn once and then disposed of.
- I have a general ennui about most things
- Disposable is a term that shouldn't be used within fashion unless the garments are completely biode gradable and unharmful to the environment
- Clothing shouldn't be disposable however I feel instagram / influencers really encourage this dispos able mentality.
- Fashion and clothing should not be disposable. Peoples attitudes need to change.
- I don't by with the intent to discard. If they are 'disposable' it feels as though the item is cheap, using lower cost materials that are usually bad for the environment.
- It depends slightly on the association (e.g. judge differently for fashion Vs bottled water), however the idea of 'wastefulness' (however that's spelt!) is something I don't like, and disposable often correlates to that
- Seems wasteful
- Hate the idea of waste/ impulse buying. I try to by less but buy things I know will last/ I will wear alot.
- I do not agree that clothing should be categorised as 'disposable' - it should either be good enough quality that if I no longer have a need for it, I can rehome it in good faith. Otherwise, I literally wear things until they are worn out and will then often use them as rags for cleaning or then they can finally go in the bin.
- There is no need for items of fashion to be disposable. If we shopped smarter and knew where to buy stylish and durable items then we wouldn't need to throw things away.
- If someone described my clothes as disposable I would feel uncomfortable. I think describing clothing as disposable encourages consumerism and unethical shopping.
- I try to avoid things that are thrown away quickly
- Clothing creates a sufficient enough carbon footprint that considering it disposable is needlessly detri mental to the environment
- I hate the casual disregard of environmental concerns.
- It fills land fills unnecessarily
- Because the commercial methods of disposing clothing responsibly are not as advance as they should be.

Q11. On average, how long do you expect each of the following items to last:

Answer Choice		1 Month or less	6 Months - 1 year	2-3 years	4-5 Years	6-7 years	8-9 Years	+ 10 years	Response Total
1	Coat	0	1	16	39	22	8	40	126
2	Dress	0	7	37	41	18	5	15	123
3	Jeans	0	6	42	34	16	6	17	121
4	Shirt	1	9	54	39	13	1	8	125
5	T-shirt	2	17	62	25	6	0	9	121
6	Under-wear	1	31	67	17	2	0	4	122
answered									120

Appendix Table 11: Consumer Survey Results Question 11.

10.3 Keracol Lab Results

10.3.1 Keracol: Wash Fastness Blackcurrant Powder

Tests conducted on Casein fibres and casein fabric.

Dyeing conditions:

- T = 60°C
- t = 30 min
- pH2/pH4/Ph6
- 1%omf, 5%omf Blackcurrant powder
- 0%, 1%omf Alum (Aluminium potassium sulphate)
- LR = 1:7

Samples:

- 6x 1%omf fabric
- 6x 1%omf fibres
- 6x 5%omf fabric
- 6x 5%omf fibres

Rinsing after dyeing

- Rinse with or without squeezing the fibres/fabric
- Rinse time: 3sec, 30sec, 60sec

Wash-fastness (wash Tec)

- 4g wool detergent (Woolite) in 1L water
- 150ml washing solution
- 30°C
- 30min

Dyeing machine: Ugolini Redkrome II
Spectrophotometer: Datacolor 500

Key Points (Fibres):

- BC powder doesn't stain the multifibre fabric at pH2 and pH2+Al.
- At pH4 and pH4+Al slight stain on Reg. cellulose, cotton.
- At pH6+Al slight stain on Reg. cellulose, cotton.

Key Points (Fabric):

- BC powder stains the multifibre fabric.
- At pH2 and pH2+Al Reg. cellulose, cotton.
- At pH4 and pH4+Al Slight stain on cotton.
- At pH6 and pH6+Al Slight stain on cotton.

Blackcurrant Powder: Pre-wash Colour Comparison

Appendix Figure 1: Casein yarns dyed with BCP, comparison of colour before washing.

Immediately after dying, the colours of the fibres and fabrics demonstrated deeper shades of pink and purple. Upon rinsing (prior to colour testing) these colours were altered and quickly changed to shades of blue, demonstrating an increased alteration in pH.

Appendix Figure 2: Casein fabric dyed with BCP, comparison of colour before washing.

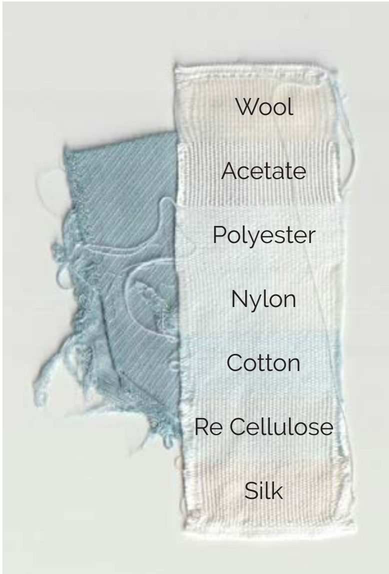
Sample 1:
pH2 T=60C
5%omf BCP

Appendix Figure 3: Sample 1 BCP wash-fastness test strip.

Sample 2:
pH2 T=60C
5%omf BCP
1%omf Alum

Appendix Figure 4: Sample 2 BCP wash-fastness test strip.

Sample 3:
pH2 T=60C
5%omf BCP

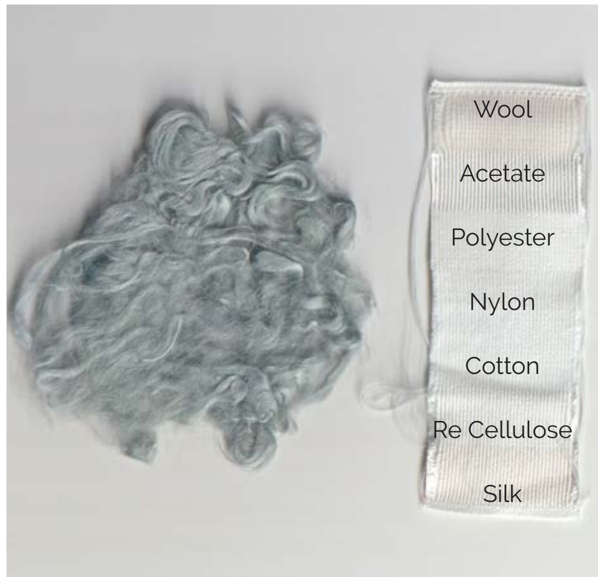


Appendix Figure 5: Sample 3 BCP wash-fastness test strip.

Sample 4:
pH2 T=60C
5%omf BCP
1%omf Alum

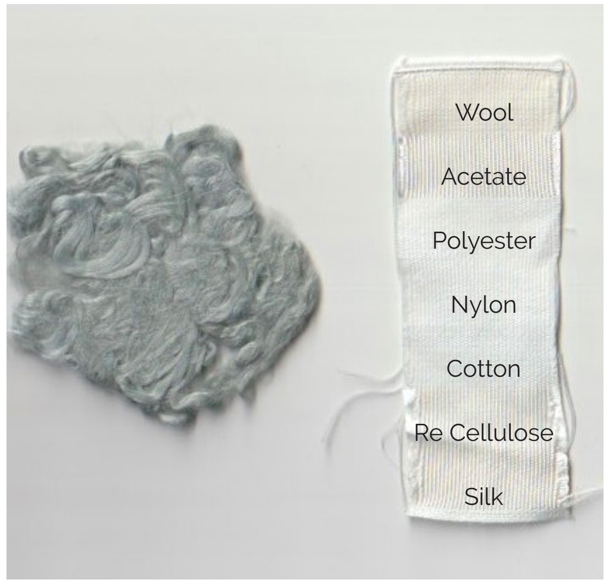
Appendix Figure 6: Sample 4 BCP wash-fastness test strip.

Sample 5:
pH4 T=60C
5%omf BCP



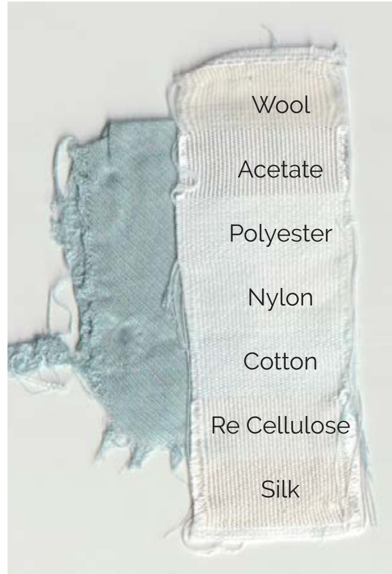
Appendix Figure 7: Sample 5 BCP wash-fastness test strip.

Sample 6:
pH4 T=60C
5%omf BCP
1%omf Alum



Appendix Figure 8: Sample 6 BCP wash-fastness test strip.

Sample 7:
pH4 T=60C
5%omf BCP

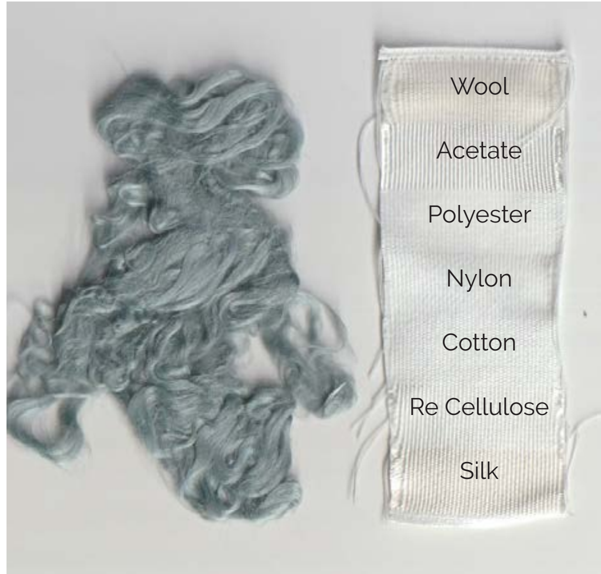


Appendix Figure 9: Sample 7 BCP wash-fastness test strip.

Sample 8:
pH4 T=60C
5%omf BCP
1%omf Alum

Appendix Figure 10: Sample 8 BCP wash-fastness test strip.

Sample 9:
pH6 T=60C
5%omf BCP



Appendix Figure 11: Sample 9 BCP wash-fastness test strip.

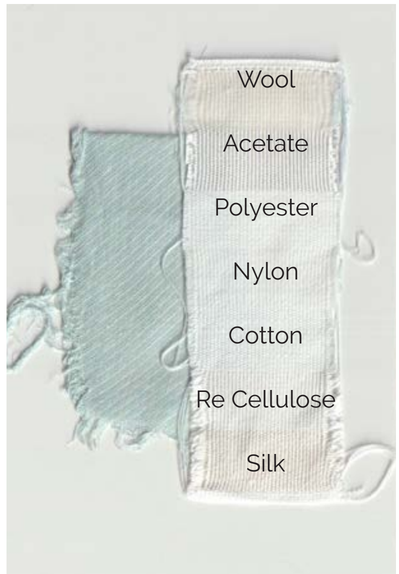
Sample 10:
pH6 T=60C
5%omf BCP
1%omf Alum

Appendix Figure 12: Sample 10 BCP wash-fastness test strip.

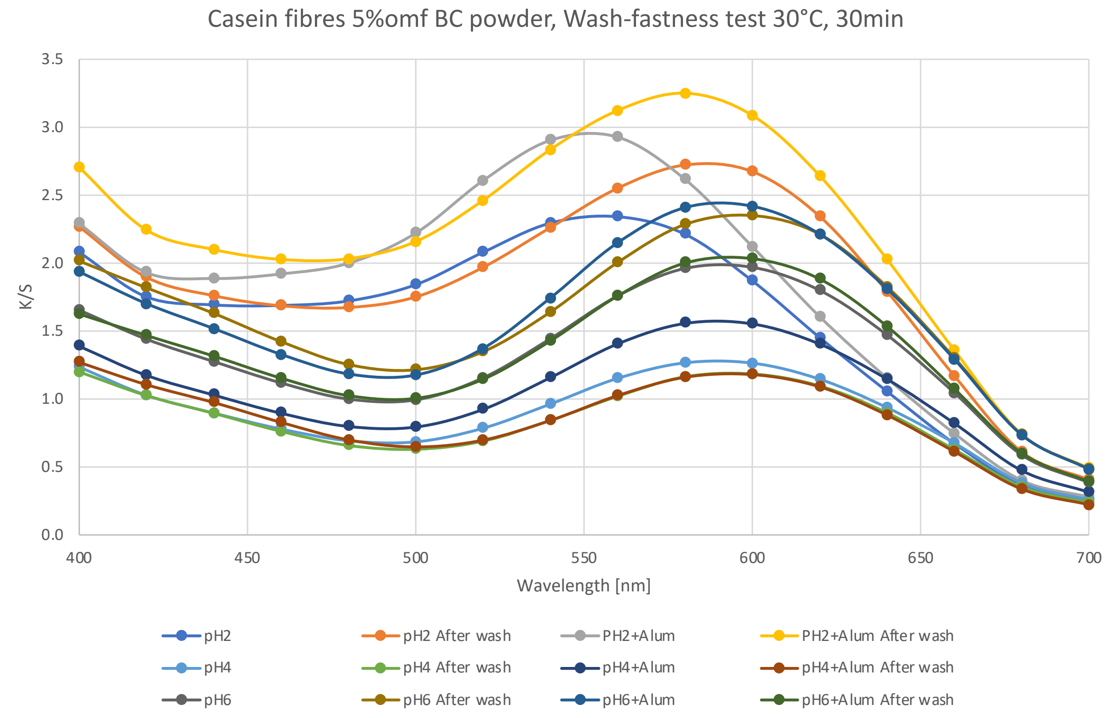
Sample 11:
pH6 T=60C
5%omf BCP

Appendix Figure 13: Sample 11 BCP wash-fastness test strip.

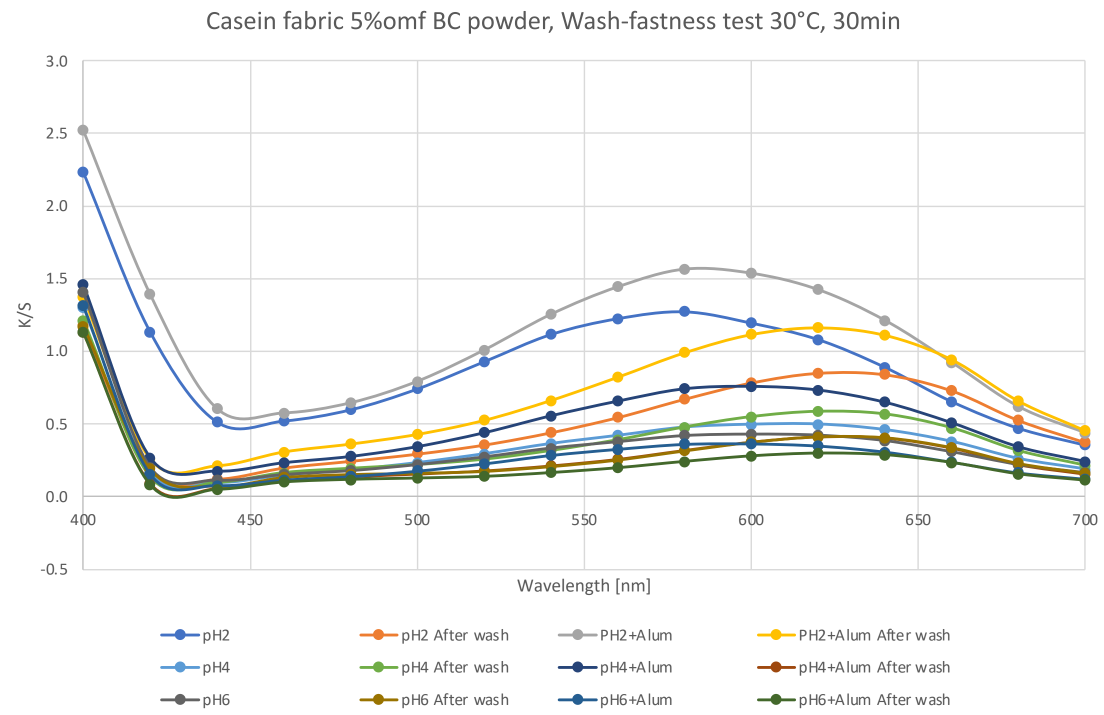
Sample 12:
pH6 T=60C
5%omf BCP
1%omf Alum



Appendix Figure 14: Sample 12 BCP wash-fastness test strip.



Appendix Chart 1: Casein fibres 5%omf BCP, wash-fastness test results @30°C for 30mins.



Appendix Chart 2: Casein fabric 5%omf BCP, wash-fastness test results @30°C for 30mins.

10.3.2 Keracol: Wash Fastness Blackcurrant Skins

Tests conducted on Casein fibres and casein fabric.

Dyeing conditions:

- T = 60°C
- t = 30 min
- pH2/pH4/Ph6
- 7.84% w/w BC skins (equivalent to 5%omf BC powder)
- 0%, 1%omf Alum (Aluminium potassium sulphate)
- LR = 1:7

Samples:

- 6x 5%omf fabric
- 6x 5%omf fibres

Rinsing after dyeing

- Rinse with or without squeezing the fibres/fabric
- Rinse time: 3sec, 30sec, 60sec

Wash-fastness (wash Tec)

- 4g wool detergent (Woolite) in 1L water
- 150ml washing solution
- 30°C
- 30min

Dyeing machine: Ugolini Redkrome II
Spectrophotometer: Datacolor 500

Key Points (Fibres):

- pH2 and pH2+Al – very light blue stain on reg.cellulose and cotton, yellow stain on nylon.
- pH4 and pH4+Al – light blue stain on reg.cellulose and cotton, yellow stain on nylon.
- pH6 and pH6+Al – blue stain on reg.cellulose and cotton, yellow stain on nylon.

Key Points (Fabric):

- pH2 and pH2+Al – blue stain on reg.cellulose and cotton, yellow stain on nylon.
- pH4 and pH4+Al – blue stain on reg.cellulose and cotton, yellow stain on nylon.
- pH6 and pH6+Al – blue stain on reg.cellulose and cotton, yellow stain on nylon.

Blackcurrant Skins: Pre-wash Colour Comparison

Appendix Figure 15: Casein yarns dyed with BCS, comparison of colour before washing.

As with the BCP dyed materials, the colours of the fibres and fabrics initially demonstrated deeper shades of pink and purple. Upon rinsing (prior to colour testing) these colours were altered and quickly changed to shades of blue, demonstrating an increased alteration in pH.

Appendix Figure 16: Casein fabric dyed with BCS, comparison of colour before washing.

Sample 1:
pH2 T=60C
7.84% w/w BCS

Appendix Figure 17: Sample 1 BCS wash-fastness test strip.

Sample 2:
pH2 T=60C
7.84% w/w BCS
1%omf Alum

Appendix Figure 18: Sample 2 BCS wash-fastness test strip.

Sample 3:
pH2 T=60C
7.84% w/w BCS

Appendix Figure 19: Sample 3 BCS wash-fastness test strip.

Sample 4:
pH2 T=60C
7.84% w/w BCS
1%omf Alum

Appendix Figure 20: Sample 4 BCS wash-fastness test strip.

Sample 5:
pH4 T=60C
7.84% w/w BCS

Appendix Figure 21: Sample 5 BCS wash-fastness test strip.

Sample 6:
pH4 T=60C
7.84% w/w BCS
1%omf Alum

Appendix Figure 22: Sample 6 BCS wash-fastness test strip.

Sample 7:
pH4 T=60C
7.84% w/w BCS

Appendix Figure 23: Sample 7 BCS wash-fastness test strip.

Sample 8:
pH4 T=60C
7.84% w/w BCS
1%omf Alum

Appendix Figure 24: Sample 8 BCS wash-fastness test strip.

Sample 9:
pH6 T=60C
7.84% w/w BCS

Appendix Figure 25: Sample 9 BCS wash-fastness test strip.

Sample 11:
pH6 T=60C
7.84% w/w BCS

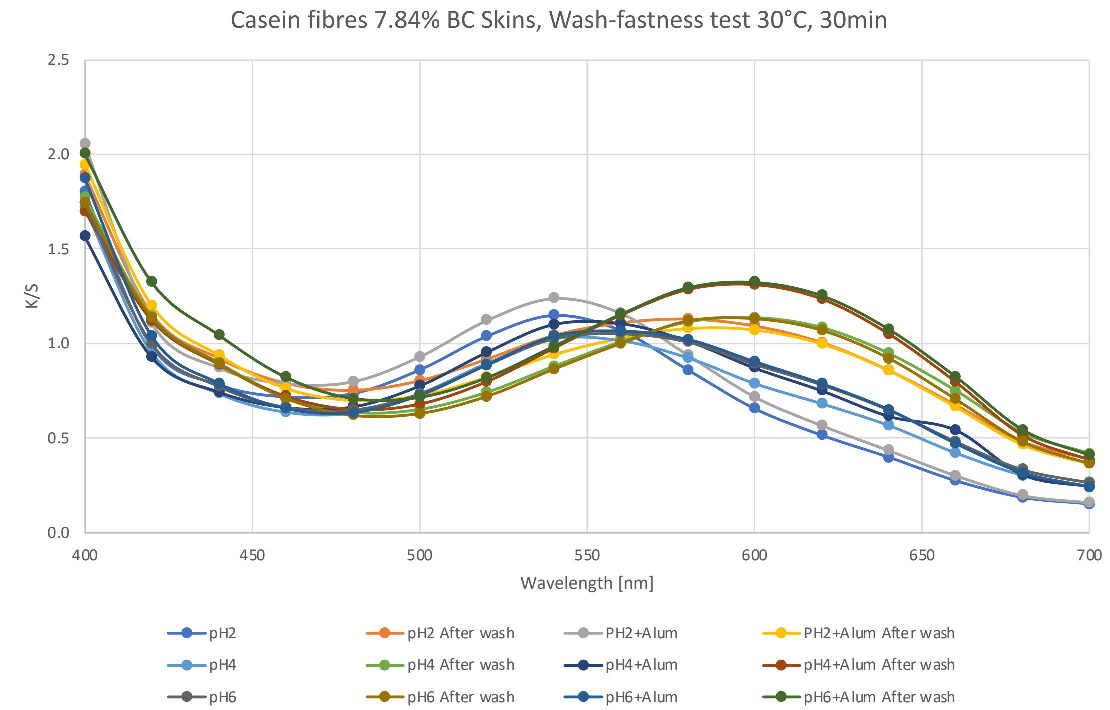
Appendix Figure 27: Sample 11 BCS wash-fastness test strip.

Sample 10:
pH6 T=60C
7.84% w/w BCS
1%omf Alum

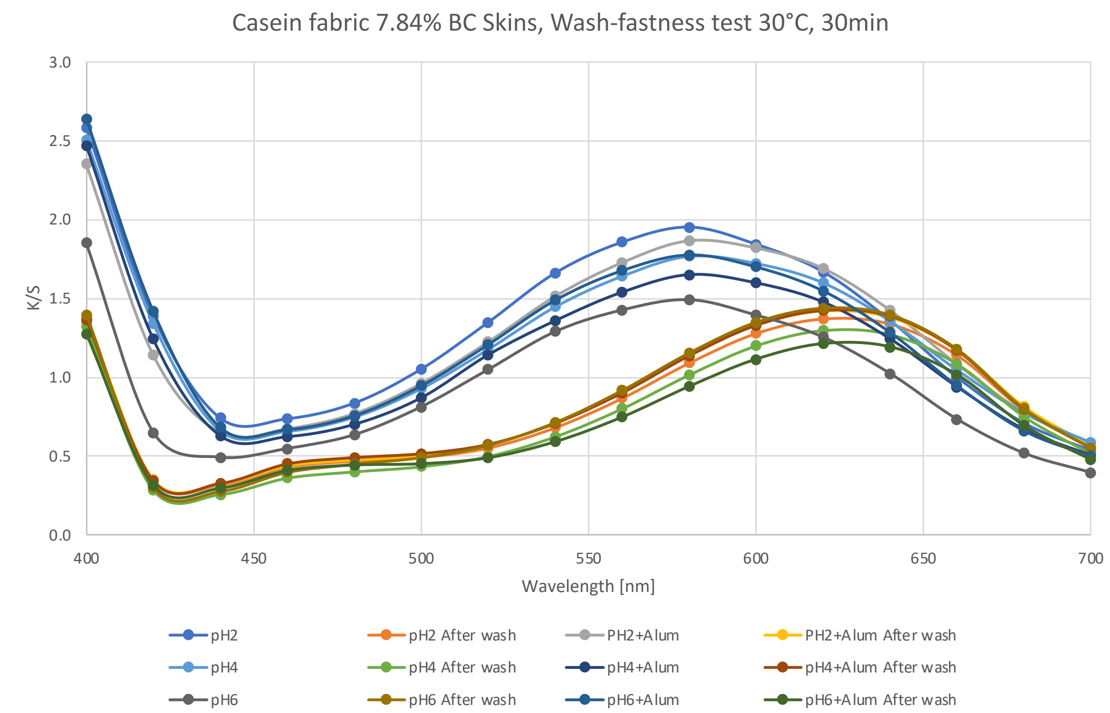
Appendix Figure 26: Sample 10 BCS wash-fastness test strip.

Sample 12:
pH6 T=60C
7.84% w/w BCS
1%omf Alum

Appendix Figure 28: Sample 12 BCS wash-fastness test strip.

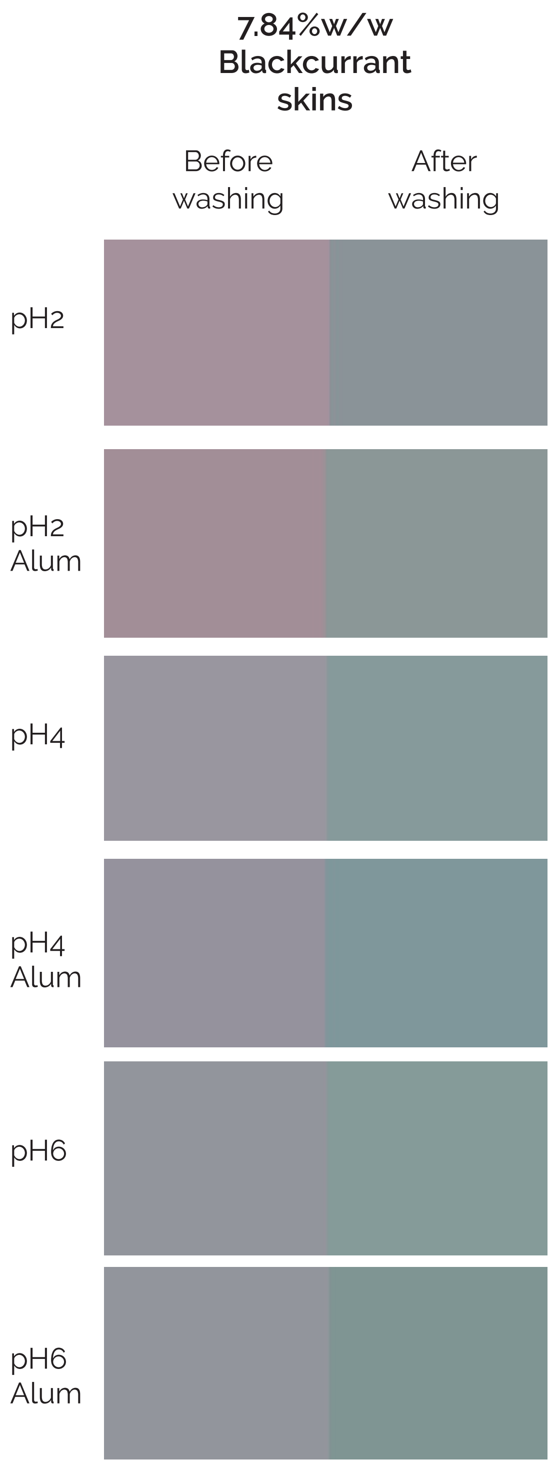


Appendix Chart 3: Casein fibres 7.84% BCS, wash-fastness test results @30°C for 30mins.

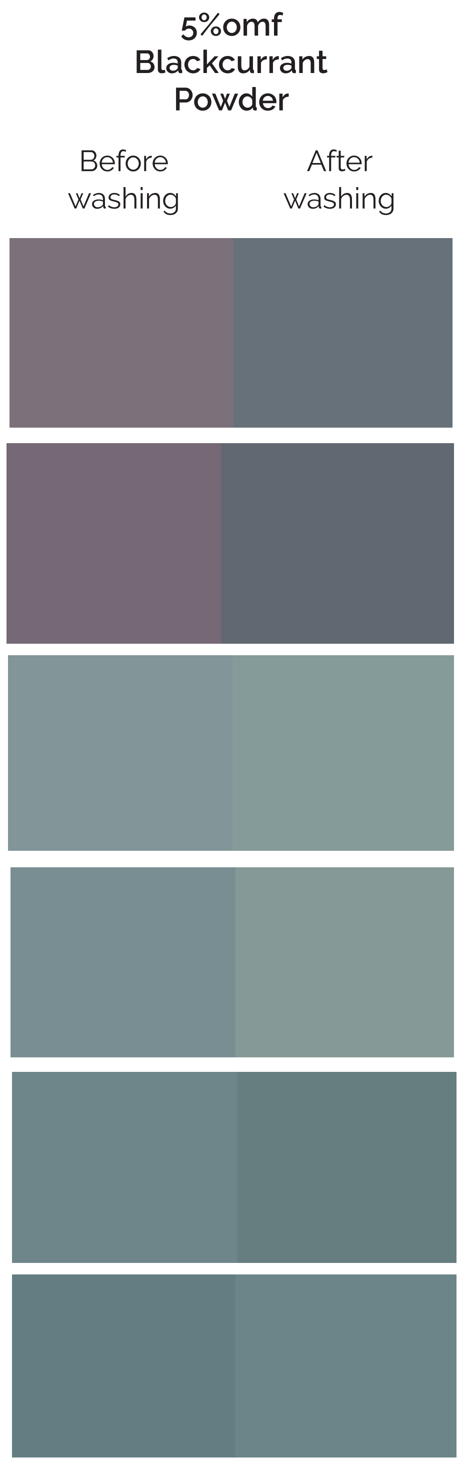


Appendix Chart 4: Casein fabric 7.84% BCS wash-fastness test results @30°C for 30mins.

Comparison Of Results: Colour Change After Washing (Fibres)

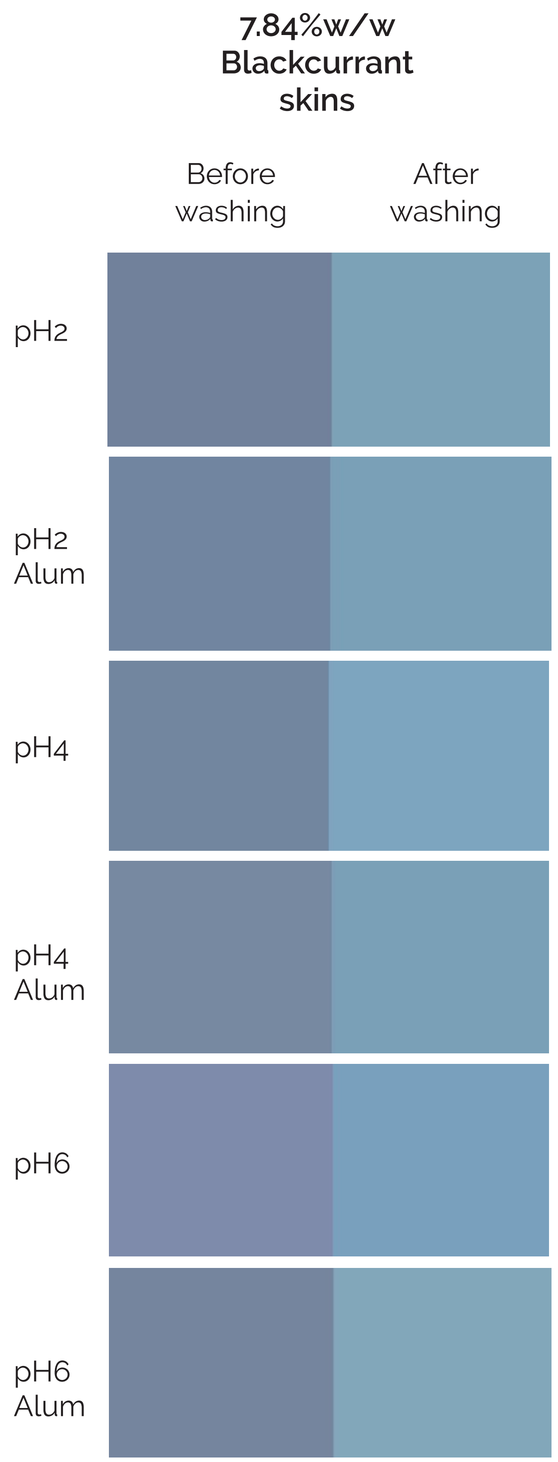


Appendix Figure 29: Colour pictures from Datacolor 500. Comparison of BCS on fibres before and after washing.

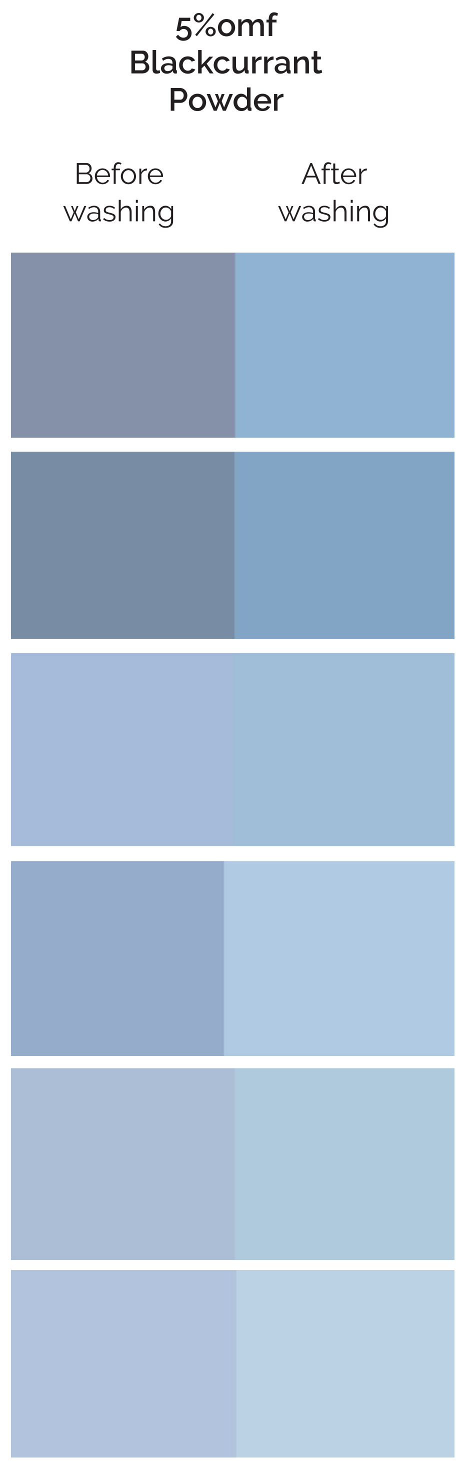


Appendix Figure 30: Colour pictures from Datacolor 500. Comparison of BCP on fibres before and after washing.

Comparison Of Results: Colour Change After Washing (Fabric)



Appendix Figure 31: Colour pictures from Datacolor 500. Comparison of BCS on fabric before and after washing.



Appendix Figure 32: Colour pictures from Datacolor 500. Comparison of BCP on fabric before and after washing.

Comparison Of Results: Wash-Fastness Test Strips (BCP)

	5% omf BCP PH2	5% omf BCP PH2 1% Alum	5% omf BCP PH4	5% omf BCP PH4 1% Alum	5% omf BCP PH6	5% omf BCP PH6 1% Alum
Fabric Results						
Wool						
Acetate						
Polyester						
Nylon						
Cotton						
Re Cellulose						
Silk						
Fibre Results						
Wool						
Acetate						
Polyester						
Nylon						
Cotton						
Re Cellulose						
Silk						

Appendix Table 12: Comparison of results, wash-fastness test strips (Blackcurrant powder)

Comparison Of Results: Wash-Fastness Test Strips (BCS)

	7.84% w/w BCS PH2	7.84% w/w BCS PH2 1% Alum	7.84% w/w BCS PH4	7.84% w/w BCS PH4 1% Alum	7.84% w/w BCS PH6	7.84% w/w BCS PH6 1% Alum
Fabric Results						
Wool						
Acetate						
Polyester						
Nylon						
Cotton						
Re Cellulose						
Silk						
Fibre Results						
Wool						
Acetate						
Polyester						
Nylon						
Cotton						
Re Cellulose						
Silk						

Appendix Table 13: Comparison of results, wash-fastness test strips (Blackcurrant skins)

10.4 Eurofins Lab Results

10.4.1 Eurofins Disintegration Test (Commercial Fibres)

This section documents the full report by Eurofins BLC, evaluating the disintegration of commercial casein fibres. These results are refered to in the thesis as Ex 18, (5.5.2).

eurofins | BLC

BLC Leather Technology Centre

A Contract Report for The University of Leeds
RCR22-099

Leather Degradation: Disintegration ISO 20200 (Modified) & PRT
13 January 2023

Eurofins | BLC Leather Technology Centre Ltd
www.blcleathertech.com

Contents

Executive Summary

The University of Leeds approached Eurofins | BLC, with regards to performing an evaluation of disintegration of a novel fibre and analyse the effects, that the material has on the quality of compost after breakdown. A single sample produced was submitted for analysis.

ISO 20200 (Modified)

The sample was analysed in accordance with BS EN ISO 20200:2015 (modified).

After 90 days thermophilic incubation (58±2°C), the following percentage disintegration was measured:

- 15.76% of the sample submitted disintegrated after 90 days thermophilic incubation.

Plant Response Testing

Composts with and without the sample provided were analysed in accordance with REAL CCS v3.1, plant response and weeds test for composted material, to evaluate the influence of degraded material on the resultant compost. The results obtained suggest that the Test sample grew more than the Blank samples in top growth, plant height, and in true leaf number. The Test sample grew less than the Control sample in top growth, plant height and in true leaf number.

Sample Reference

BLC Reference	Customer Reference	Supporting Image
Sample 1 (S1)	Not Provided	

Methodology

1. **BS EN ISO 20200:2015 (Modified)***

Please note that this method is modified. The BS EN ISO 20200:2015 standard is designed to calculate the degree of disintegration of plastic materials under simulated composting conditions in a laboratory-scale test. During this evaluation plastic samples were substituted for a novel protein fibre. Due to the structural properties of the material, an additional deviation from the standard was to place the fibres into mesh bags to enable the breakdown of the material to be measured. This may affect the validity of the method (according to the BS EN ISO 20200:2015 standard).

<u>Thermophilic Incubation Period</u>

During the thermophilic incubation period, the test sample was incubated with synthetic compost at 58±2°C for 90 days. The changes to the sample/compost mixture that were observed during this period are summarised in Table 2.

2. **Plant Response Testing***

REAL CCS v3.1, Methods for testing plant response to composted material and its contamination by weed seeds and propagules. October 2015. Method code: OFW004-006. Used for assessment of PAS 100 compost standards.

* performed by an approved subcontract partner laboratory.

Results & Discussion

BS EN ISO 20200 (Modified) Analysis - Post Thermophilic Stage

Table 1: Initial testing parameters and compost composition and evaluation

Test Requirement	Detail		
Test code number:	RCR22-099		
Sample description:	Cream coloured hairy fibres, that are hydrophilic. Thickness less than 1 mm and cut to 4-10 mm lengths for PRT and 25 mm lengths for BS EN ISO 20200		
Sample weight (M_i), in triplicate (start):	Mean: 11.87 ± 0.43 g		
Mass of reactor (M_{ri}), in triplicate (start):	Before the addition of water: 450 g	After the addition of water: 1000 g	
Test method used:	ISO 20200: 2015 (90 days at 58°C, compulsory; and then 90 days at 25°C, selected)		
Synthetic compost composition	Sawdust	1.68 kg	40%
	Rabbit feed	1.26 kg	30%
	Ripe compost	0.42 kg	10%
	Corn starch	0.42 kg	10%
	Saccharose	0.21 kg	5%
	Corn seed oil	0.17 kg	4%
	Urea	0.04 kg	1%
	Total	4.20 kg	100%
Synthetic compost evaluation (start)	Initial compost carbon: nitrogen ratio ($C:N_i$): 29:1		
	Initial compost pH value (pH_i): 5.74 (±0.10)		
	Initial compost dry matter value (DM_i): 88.8%		
	Initial compost volatile solids value (VS_i): 94.1%		
Reactor and equipment descriptions:	The reactors used were polypropylene airtight boxes, with removal lids. Box dimensions were 29.5 x 19 x 9.5 mm. The reactor has 2 x 5 mm holes. The incubator is an LTE Scientific IP250-UF. Sieves used were Endecotts Ltd 10, 5, and 2 mm sieves, using the ISO 3310-1:2000 method.		

Table 2: Testing operation, observations, and results (Thermophilic)

Test Requirement	Days from Start	Operation	
Incubation (58°C, 90 days) – observations (for all replicates):	0	Initial mass recorded	
	1,2,3,4,7,9,11,14	Weighed and restored to original mass. Mixed.	
	8,10,16,18,21,23, 25,28	Weighed and restored to original mass. No mixing done.	
	30,45	Weighed and restored to 80% of original mass. No mixing done.	
	Day 30-60 (twice a week)	Weighed and restored to 80% of original mass. No mixing done.	
	Day 60 onwards (twice a week)	Weighed and restored to 70% of original mass. No mixing done.	
	7 days	White mycelia	
	14 days	White mycelia	
	21 days	Sweet smell	
	28 days	Grey mycelia	
	35 days	White mycelia	
	42 days	Compost darkening	
	49 days	Musty smell	
	56 days	Musty smell	
	63 days	No smell	
	70 days	Musty smell	
	77 days	Sample clearly intact	
	84 days	Musty smell	
	90 days	Test end	
Mass of reactor (M_{rft}), in triplicate (thermophilic end):	Mean: 168.3 ±15.6 g		
Sample weight (M_{ft}), in triplicate (thermophilic end):	Mean: 10.00 ±0.39 g		
Sample disintegration, D_t, (thermophilic): $D_t = \left(\frac{M_i - M_{ft}}{M_i}\right) x\, 100$	15.76 ± 0.24% (84.24% *stays in the 2 mm sieve*)		
Observations for Positive Control (these were run alongside the test to check the viability of the test experiments)	Material	Approximate Disintegration Expected (%)	Approximate Experiment Disintegrated (%)
	Dog chew (Raw Hide)	98.35	100.00
	Sponge Cloth	90.62	92.27
	Cardboard	59.95	60.75
Declaration of validity of positive test	The positive test results were as expected so the test was valid		
Synthetic compost evaluation (end)	Final compost carbon: nitrogen ratio ($C:N_{ft}$): 29:1		
	Final compost pH value (pH_{ft}): 8.02 ± 0.08		

	Final compost dry matter (DM_{ft}): 94.1 %
	Final compost volatile solids (VS_{ft}): 88.5 %
Synthetic compost's decrease in volatile solids (R_t), after thermophilic: $R_t = \left(\frac{(Mr_i \, x \, DM_i \% \, x \, VS_i \%)-(M_{rft} \, x \, DM_{ft}\% \, x \, VS_{ft}\%)}{(M_{ri} \, x \, DM_i\% \, x \, VS_i\%)}\right) x \, 100$	69.00 ± 2.88 %

Equation Definitions:

M_i – Initial dry mass of the test material

M_{ft} – Final sample mass (at the end of the thermophilic stage)

M_{ri} – Initial mass of the wet synthetic waste introduced into the reactor

DM_i – Initial dry mass of the synthetic waste, expressed as a percentage divided by 100

VS_i – Initial volatile-solids content of the synthetic waste, expressed as a percentage divided by 100

M_{rft} – Final reactor mass – thermophilic

DM_{ft} – Final dry mass of the compost, expressed as a percentage divided by 100 – thermophilic

VS_{ft} – Final volatile-solids content of the compost, expressed as a percentage divided by 100 – thermophilic

The test was deemed **viable** (see the requirements below):

Test Requirement	Measured				Expected Standard
Volatile solids change	69.0 %				>30%
pH	Start:	5.74	End:	8.02	5-9
C:N ratio	Start:	29:1	End:	29:1	20:1-40:1 (at start)
Observations	The progression of the composting appeared as normal.				See ISO 20200 for definition of normal composting progression.

The average disintegration for the test sample was **15.76 ± 0.24 %** (measured as change in mass) after the thermophilic stage.

The plastic industry specification (BS EN 14995:2006[1]) that informs the requirements of EU Directive 94/62/EC, states that in terms of disintegration, a material is said to be disintegrated, in compost, if no more than 10% of the starting material is retained by a 2 mm sieve, after the thermophilic incubation period (for ISO 16929: 2019[2]).

84.24% of the test sample was retained by a 2 mm sieve after the thermophilic stage of the laboratory-scale ISO 20200 (modified) test. Therefore, if this substrate were applicable and tested against BS EN 14995:2006 requirements, this substrate (in its current state), would not be considered a promising candidate for the disintegration element of the compostability requirements.

[1] BS EN 14995:2006 Plastics. Evaluation of compostability. Test scheme and specifications

[2] ISO 16929:2019 Plastics - Determination of the degree of disintegration of plastic materials under defined composting conditions in a pilot-scale test

Post ISO 20200 (Modified) Compost Analysis - Plant Response Testing

Table 3: PRT Results

Test requirement	Detail									
Test code number:	RCR22-099									
Test method used:	REAL CCS v3.1. Methods for testing plant response to composted material and its contamination by weed seeds and propagules. October 2015. Method code: OFW004-006. Used for assessment of PAS 100 compost standards.									
Materials applied in test: Commercial compost	Sphagnum moss peat									
Blank: 'Peat' based growing medium (PBGM): Sieved substrate (SS) conductivity (B):	1.80 ± 0.19 mS m^{-1}									
The % mass/mass of <10 mm particles (H):	100 %									
Negative growth conditions and other influences (P):	0									
Total number plants expressed as % (S):	Day No.	Blank			Control			Test		
		1	2	3	1	2	3	1	2	3
	10	100	90	100	100	100	100	90	100	100
	14	100	90	100	100	100	100	90	100	100
	28	100	90	100	100	100	100	90	100	100
Declaration of validity of the test (T):	The number of germinated seedlings was more than 27 (29), the test is valid									
Abnormalities - all (U):	No abnormalities were present in the Blank, Control or Test samples.									
Declaration of presence or absence of any abnormalities not present (V):	No abnormalities were present in the Blank, Control or Test samples.									
Declaration of presence or absence of any abnormalities present - validity (W):	No abnormalities were present in the Blank, Control or Test samples.									
The total top growth fresh mass of Blank at 28 days (X_1):	32.8, 34.5, 35.3 g									
The total top growth fresh mass of Control at 28 days (X_2):	55.3, 69.6, 61.4 g									

Test requirement	Detail
The total top growth fresh mass of Test at 28 days (Y):	52.4, 32.6, 49.6 g
The mean top growth fresh mass of Blank at 28 days (Z1):	3.54 g
The mean top growth fresh mass of Control at 28 days (Z2):	6.21 g
The mean top growth fresh mass of Test per plant at 28 days (AA):	4.64 g
The mean top growth fresh mass of Test % of Blank top growth fresh mass per plant at 28 days (BB):	131.19%
The mean top growth fresh mass of Test % of Control top growth fresh mass per plant at 28 days:	74.74%
The mean top growth fresh mass per plant for all Blanks at 28 days and Declaration (CC):	The average plant mass, after 28 days exceeded 2.0 g per plant (3.54 g), thus the test is valid.
Number of weeds per litre of test (as received) after 28 days (FF):	0.33

Test Summary

The test commenced on 28/11/2022 and ended on the 26/12/2022.

The germination number of seedlings, as seen in the Blank growth trays, after 14 days were more than the number that renders the test invalid. Thus, the test from that point onwards was classified as valid.

The number of abnormalities seen in the Blank growth trays, after 28 days was not enough to render the test invalid. Thus, the test from that point onwards was classified as valid. After 28 days, the top growth fresh mass (TgFM) of all Blank plant trays, divided by the total number of plants in all three trays equalled 3.54 g. The amount was higher than the 2.0 g (minimum) that the test needs to be rendered valid. Thus, the test from that point onwards was classified as valid.

After 28 days, the mean TgFM of the Test trays (per plant) was more than the mean TgFM of the Blank trays (per plant). The mean TgFM of the Test trays (per plant) was less than the mean TgFM of the Control trays (per plant). The mean TgFM of the Test trays (per plant) as a percentage of the mean TgFM of the Blank trays (per plant) was 131.19%. The mean TgFM of the Test trays (per plant) as a percentage of the mean TgFM of the Control trays (per plant) was 74.74%.

The Test plants showed no evidence of deformations.

In conclusion, the Test sample grew more than the Blank samples in top growth, plant height, and in true leaf number (Appendix 2). The test sample grew less than the Control sample in top growth, plant height and in true leaf number (Appendix 2).

Appendix 1 - ISO 20200 (Modified) Supporting Images

Figure 1: Samples at the start cut into shorter pieces

Figure 2: Samples in mesh bags on synthetic compost at the start

Figure 3: Samples at Day 28 showing compression and discolouration

Figure 4: Samples at Day 49 showing detail of discolouration and compression

Figure 5: Sample on Day 70

Figure 6: Sample on Day 90

Appendix 2 - Digital Images of Growth in Plant Response Testing

(1) (2) (3)

Figure 7: Comparison of substrate colour and appearance between 1) Blank 2) Control and 3) Test Sample growth substrates on Day 1

Figure 8: Test sample plant growth on Day 14

Figure 9: Blank sample growth on Day 14

(1) (2) (3)

Figure 10: Comparative growth of 1) Blank 2) Control or 3) Test Sample plants at Day 28 showing the tallest and shortest plant out of the triplicates. Blank image has been adjusted to correct for scale.

Figure 11: Comparative growth of the Test Sample plant triplicate set at Day 28 showing the range of plant growth.

Figure 12: Image showing the vitality of the Test Sample plant.

Figure 13: Comparative growth of the Blank plant triplicate set at Day 28 showing the range of plant growth.

Figure 14: Image showing the vitality of the Blank plant.

Figure 15: Comparative growth of the Control plant triplicate set at Day 28 showing the range of plant growth.

Figure 16: Image showing the vitality of the Control plant.

10.3.4 Disintegration Test (Monofilament)

This section documents the second full report by Eurofins BLC, evaluating the disintegration of lab-produced casein monofilament. These results are refered to in the thesis as Ex 19, (5.5.3).

eurofins | BLC

BLC Leather Technology Centre

The University of Leeds

RCR22-170

Novel Fibre Disintegration Testing: ISO 20200 (Modified)

24 April 2023

Eurofins | BLC Leather Technology Centre Ltd
www.blcleathertech.com

Contents

Executive Summary

The University of Leeds approached Eurofins | BLC, with regards to performing an evaluation of disintegration of a novel fibre. A single sample produced was submitted for analysis.

ISO 20200 (Modified)

The sample was analysed in accordance with BS EN ISO 20200:2015 (modified).

After 45 days thermophilic incubation (58±2°C), the following percentage disintegration was measured:

- 100% of the sample submitted disintegrated after 45 days thermophilic incubation.

Sample Reference

BLC Reference	Customer Reference	Supporting Image(s)
Sample 1 (S1)	Not provided	

Methodology

1. **BS EN ISO 20200:2015 (Modified)***

Please note that this method is modified. The BS EN ISO 20200:2015 standard is designed to calculate the degree of disintegration of plastic materials under simulated composting conditions in a laboratory-scale test. During this evaluation plastic samples were substituted for a novel protein fibre. Due to the structural properties of the material, an additional deviation from the standard was to place the fibres into mesh bags to enable the breakdown of the material to be measured. This may affect the validity of the method (according to the BS EN ISO 20200:2015 standard).

<u>Thermophilic Incubation Period</u>

During the thermophilic incubation period, the test sample was incubated with synthetic compost at 58±2°C for 90 days. The changes to the sample/compost mixture that were observed during this period are summarised in Table 2.

Sufficient disintegration was observed in the thermophilic stage and therefore, the test was terminated after 45-days, and the mesophilic phase was not required.

*Please note these tests were performed by an approved subcontract partner laboratory.

Results & Discussion

BS EN ISO 20200 (Modified) Analysis – Post Thermophilic Stage

Table 1: Initial testing parameters and compost composition and evaluation

Test Requirement	Detail		
Test code number:	RCR22-170		
Sample description:	Off-white, coarse spun fibres		
Sample weight (M_i), in triplicate (start):	Mean: 24.16 g (±2.66 g)		
Mass of reactor (M_{ri}), in triplicate (start):	1000 g		
Test method used:	ISO 20200: 2015 (90 days at 58°C, compulsory; and then 90 days at 25°C, selected)		
Synthetic compost composition	Sawdust	1.68 kg	40%
	Rabbit feed	1.26 kg	30%
	Ripe compost	0.42 kg	10%
	Corn starch	0.42 kg	10%
	Saccharose	0.21 kg	5%
	Corn seed oil	0.17 kg	4%
	Urea	0.04 kg	1%
	Total	4.20 kg	100%
Synthetic compost evaluation (start)	Initial compost carbon: nitrogen ratio ($C:N_i$): 27:1		
	Initial compost pH value (pH_i): 5.810 (±0.06)		
	Initial compost dry matter value (DM_i): 86.8%		
	Initial compost volatile solids value (VS_i): 92.1%		
Reactor and equipment descriptions:	The reactors used were polypropylene airtight boxes, with removal lids. Box dimensions were 29.5 x 19 x 9.5 mm. The reactor has 2 x 5 mm holes. The incubator is an LTE Scientific IP250-UF. Sieves used were Endecotts Ltd 10, 5, and 2 mm sieves, using the ISO 3310-1:2000 method.		

Table 2: Testing operation, observations, and results (Thermophilic)

Test Requirement	Days from Start	Operation	
Incubation (58°C, 90 days) – observations (for all replicates):	0	Initial mass recorded	
	1,2,3,4,7,9,11,14	Weighed and restored to original mass. Mixed.	
	8,10,16,18,21,23, 25,28	Weighed and restored to original mass. No mixing done.	
	30,45	Weighed and restored to 80% of original mass. No mixing done.	
	Day 30-60 (twice a week)	Weighed and restored to 80% of original mass. No mixing done.	
	Day 60 onwards (twice a week)	Weighed and restored to 70% of original mass. No mixing done.	
	7 days	Sample disintegrating	
	14 days	Sample not visible	
	21 days	Compost darkening	
	28 days	Musty smell	
	35 days	Earthy smell	
	42 days	Earthy smell	
	49 days	Test terminated	
	56 days	Test terminated	
	63 days	Test terminated	
	70 days	Test terminated	
	77 days	Test terminated	
	84 days	Test terminated	
	90 days	Test terminated	
Mass of reactor (M_{rft}), in triplicate (thermophilic end):	583.57 ± 1.58 g		
Sample weight (M_{ft}), in triplicate (thermophilic end):	Mean: 0.00 g		
Sample disintegration, D_t, (thermophilic): $D_t = \left(\frac{M_i - M_{ft}}{M_i}\right) x\ 100$	100% (0% stays in the 2mm sieve)		
Observations for positive control	Material	Approximate disintegration expected (%)	Approximate Experiment Disintegrated (%)
	Dog chew (raw hide)	98.35	100.00
	Sponge cloth	90.62	92.27
	Cardboard	59.95	60.75
Declaration of validity of positive test	The positive test results were as expected so the test was valid.		
Synthetic compost evaluation (end)	Final compost carbon: nitrogen ratio ($C:N_{ft}$): 19:1		
	Final compost pH value (pH_{ft}): 7.92 (±0.11)		
	Final compost dry matter (DM_{ft}): 90.7 %		
	Final compost volatile solids (VS_{ft}): 83.7 %		

Synthetic compost's decrease in volatile solids (R_t), after thermophilic: $R_t = \left(\frac{(Mr_i \times DM_i\% \times VS_i\%) - (M_{rft} \times DM_{ft}\% \times VS_{ft}\%)}{(M_{ri} \times DM_i\% \times VS_i\%)}\right) x\ 100$	71.91% (±0.49 %)

Equation Definitions:

M_i – Initial dry mass of the test material

M_{ft} – Final sample mass (at the end of the thermophilic stage)

M_{ri} – Initial mass of the wet synthetic waste introduced into the reactor

DM_i – Initial dry mass of the synthetic waste, expressed as a percentage divided by 100

VS_i – Initial volatile-solids content of the synthetic waste, expressed as a percentage divided by 100

M_{rft} – Final reactor mass – thermophilic

DM_{ft} – Final dry mass of the compost, expressed as a percentage divided by 100 – thermophilic

VS_{ft} – Final volatile-solids content of the compost, expressed as a percentage divided by 100 – thermophilic

The test was deemed **viable** (see the requirements below):

Test Requirement	Measured				Expected Standard
Volatile solids change	71.9%				>30%
pH	Start:	5.81	End:	7.92	5-9
C:N ratio	Start:	27:1	End:	19:1	20:1-40:1 (at start)
Observations	The progression of the composting appeared as normal.				See ISO 20200 for definition of normal composting progression.

The average disintegration for the test sample was **100%** (measured as change in mass) after the thermophilic stage. There is no leather/textile industry specification as such that defines the desirable degree of disintegration.

The plastic industry specification (BS EN 14995:2006[1]) that informs the requirements of EU Directive 94/62/EC, states that in terms of disintegration, a material is said to be disintegrated, in compost, if no more than 10% of the starting material is retained by a 2 mm sieve, after the thermophilic incubation period (for ISO 16929: 2019[2]).

0% of the test sample was retained by a 2 mm sieve after the thermophilic stage of the laboratory-scale ISO 20200 (modified) test. Therefore, if this substrate were applicable and tested against BS EN 14995:2006 requirements, this substrate (in its current state), could be a promising candidate for the disintegration element of the compostability requirements.

[1] BS EN 14995:2006 Plastics. Evaluation of compostability. Test scheme and specifications

[2] ISO 16929:2019 Plastics - Determination of the degree of disintegration of plastic materials under defined composting conditions in a pilot-scale test

Appendix 1 – ISO 20200 (Modified) Supporting Images (Start)

Figure 1: Sample before starting the thermophilic stage.

Figure 2: Sample and synthetic compost at start. Samples were places in bags to track degradation.

Appendix 2 - ISO 20200 (Modified) Supporting Images (End)

Figure 3: Samples at day 7 showing material dissolving and seeping through mesh.

Figure 4: Sample at day 14 complete disintegration leaving empty bags.

10.5 Weave Reports

10.5.1 Weaving With Commercial Fibres

This section documents the first full report by Hannah Auerbach George and provides an evaluation of the properties and usability of commercial casein yarns. These results have been referred to in the thesis as Ex 15, (5.4.3).

HANNAH AUERBACH

Hannah Auerbach

Date: 05.04.22

Marie Stenton

Detail:

Weaving with Bellatrista milk yarn fibres notes:

Initial observations -

The yarn is soft, smooth and lustrous. It comes in a variety of weights and appears strong enough for both warp and weft. The yarn does appears to be quite fluffy despite the silkiness of the fibres. Dyed yarns have a smoother quality.

Dyeing -

The yarn dyes easily, taking colour well and absorbing quickly. The yarn did not become overly tangled or difficult to manage, even when agitated, similar to silk and unlike wool. The dyed yarn became stiff and smooth once dried but soon became supply again after winding. No obvious damage/degradation caused by dyeing.

Warping - The yarn warped easily and smoothly with no breakages. Minimal fibres were released while warping. The yarn is quite bulky for the count so filled the warping board quickly. The yarn was easy to transfer to the loom, wound on smoothly and threaded easily. Despite the silky texture the yarn tied on well; the knots did not slip loose. As described, the yarn is silky yet textured enough to provide grip.

Weaving -

The initial samples wove easily. The yarn gave a good clean shed. After some time however, the yarns began to give out and break, particularly at the edges of the warp. Breakages were solved by tying in new ends. However, the warp quality continued to deteriorate. Large amounts of fibres were released while weaving which gathered around the loom. To resolve this, the warp was cut off, pulled forward and retied. The position of the beater was changed to reduce friction on the warp yarns. The shafts were also lowered to reduce friction. The following samples were woven with a looser tension and the warp was more regularly advanced to reduce strain on any specific section. These actions seemed to resolve any issues with tensile strength and there were no more breakages in any samples. There were also considerably less fibres produced.

1

Finishing -

Samples 1, 2, 4, 5, 6 were heat pressed at 120 degrees. The yarn gave off no steam indicating no moisture in the yarn (as sometimes seen with wool). The yarn became 'fused' or almost 'bonded' creating a flat sheeny surface. This is similar to what is described about other protein yarns, (Ardil) they do not felt but they can 'weld'. The samples were then cut and some edges glued to hold there position.

Conclusion -

The yarn is easy to work with, has a luxurious handle and creates lovely fabrics. Attention must be paid to handling and set up of equipment to avoid excess friction being placed on the yarn. However, with these mitigations in place the yarn is easy to work with. The yarn is prone to shed fibres but this can be controlled by reducing friction. The yarn also takes dye beautifully. However, my next concern would be to see how the fabric perform in a rub testing. Given the problems weaving with high tension, I would expect these fabrics to perform poorly in rub testing, they are likely to weaken quickly or produce pilling/ shed fibres.

Samples Notes

Warp - Straight draft across 24 shafts. Yarn 4, Ecru 24/4. 24 Ends per inch. 12 dent reed. 12 inches wide.

Sample 1 - 3 yarns used: Pick and pick, Bulky weight yarn: 2.A, 2.B & 3. Structure 2. Fringing using bulky weight yarn created on edges.

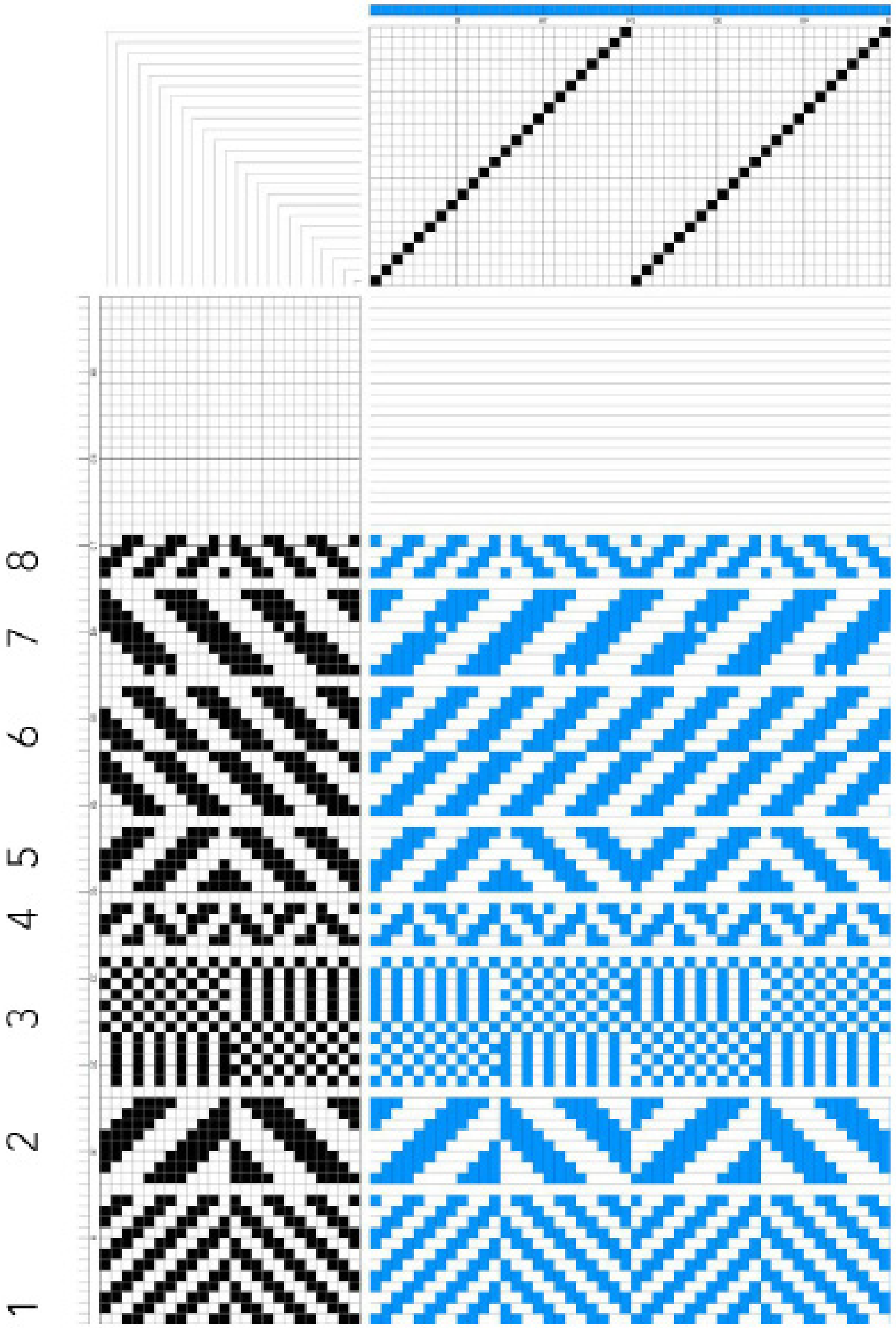
Sample 2 - 1 yarn used: Single pick, Laceweight yarn: 1.B. Structure 4. Small herringbone design. Some difficulties with yarn breaking throughout.

Sample 3 - 4 yarns used: Pick and pick, Bulky weight yarn: 2.A & 3, 2.B & 1.A. Structure 5, occasionally reversed. Left un-pressed for loftier texture.

Sample 4 - 1 yarn used: Single pick, Lace weight yarn: 1.D. Structure 6. Kercaol dyed yarn.

Sample 5 - 3 yarns used: Pick and pick, Bulky weight yarn: 2.B, Laceweight yarn 1.C & 3. Structure 7.

Sample 6 - 2 yarns used: Single pick, Laceweight yarn 1.C. Yarn 3. Structure 8, occasionally reversed.


1
2
3
4
5
6
7
8

4


Yarn 1.A
Avo Dyed
Laceweight
Yarn 1.B
Avo Dyed
Laceweight
Yarn 1.C
Onion Dyed
Laceweight
Yarn 1.D
Keracol Dye
Laceweight
Yarn 2.A
Avo Dyed
Bulky
Yarn 2.B
Ecru
Bulky
Yarn 3
Ecru
16/4
Yarn 4
Ecru
24/4 Warp

5

10.5.2 Weaving With Monofilament

This section documents the second full report by Hannah Auerbach George and provides an evaluation of the properties and usability of lab-produced casein monofilament. These results have been referred to in the thesis as Ex 16, (5.4.4).

HANNAH AUERBACH

Hannah Auerbach

Date: 06.10.23

Marie Stenton

Detail:

Weaving with lab-spun casein filament yarn notes:

Initial observations -

The yarn is brittle and has become coiled around the bobbins it has been stored on. It is liable to spring off the bobbin in coiled form. This combined with the slightly brittle quality makes it more difficult to work with. This yarn being a monofilament construction meant it was quite different to the spun fibre yarn used in previous sampling. It was stiffer and more delicate leading to a very different sample. It was also significantly finer, meaning the final samples were more delicate and lightweight.

Batches -

The yarn was provided in 4 separate batches, each using different amounts of dye in the dope.

Batch 1 – Was undyed and flexible, it wove well.

Batch 2 – Was undyed and more brittle that batch one, it was more difficult to work with.

Batch 3 – Was dyed, it had a pale colour and wove fairly well but was more liable to snapping than yarn 1.

Batch 4 – Was dyed, it had the darkest colour and wove well.

Warping – Due to the delicacy and brittle nature of the casein yarn it was decided to sample with weft only. Therefore, we chose to make a warp from another protein yarn, 2/120 silk yarn. This allowed us to explore the properties of the yarn as a weft.

Weaving -

An initial sample was made to access the weaving quality of each yarn. Then four further samples were developed to demonstrate different properties of the yarns and explore structure. There we no problems with the warp as a strong silk 2/120 was used. The weft did break a few time during the weaving process so less brittle batches were selected for the sampling process. The speed and yarn tension was adjusted for to accommodate the delicate nature of the yarn. The yarn was rewound onto smaller bobbins to avoid the potential for spring off the bobbin.

Finishing -

Minimal finishing was used on the samples as they were so delicate. The samples were cut and some edges glued to hold their position. They were mounted on card to support the samples and to highlight the flexible nature the monofilament structure added.

Conclusion -

The yarn was brittle and yet flexible with a texture not dissimilar to vermicelli rice noodles. However, using a silk warp gave a soft and pliable material. The material had little drape but did have a beautiful sheen and transparency. Considering the R&D process required to produce the yarn samples the weaving was a great success and shows great potential for further development of the material. Next steps would include improving the tensile strength of the filament and reducing the brittleness. Long-term development could include turning the monofilament into short fibres which could then be spun.

Samples Notes

Warp - Straight draft across 16 shafts. 2/120s silk yarn, 3DPI, 30 Reed

Sample 1 – Weft Batch 3 – 2/2 twill

Sample 2 – Weft Batch 1 – Honeycomb structure

Sample 3 – Weft Batch 4 – Plain weave with floats

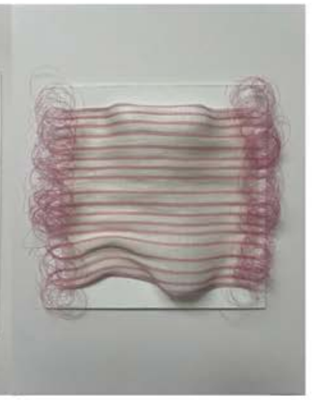
Sample 4 - Weft Batch 1,4 – Satin

Sample 1

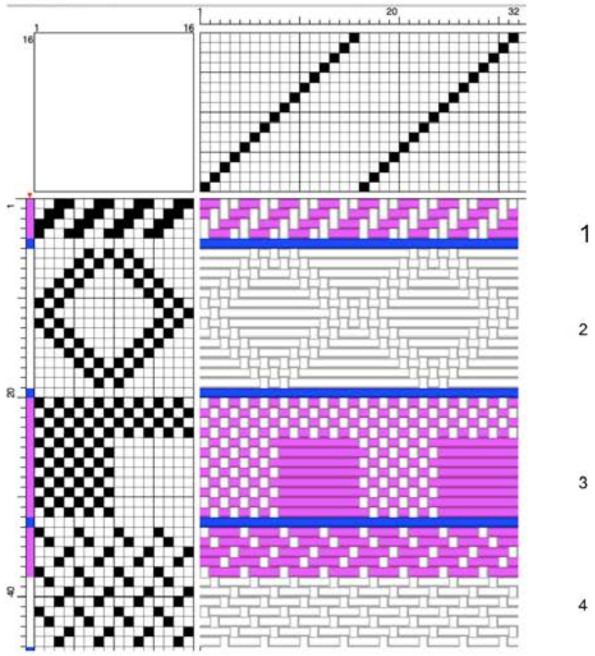
Sample 2

2

Sample 3



Sample 4



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10.6 Publications

10.6.1 Paper 1: The Potential For Regenerated Protein Fibres Within A Circular Economy: Lessons From The Past Can Inform Sustainable Innovation In The Textiles Industry

sustainability MDPI

Review

The Potential for Regenerated Protein Fibres within a Circular Economy: Lessons from the Past Can Inform Sustainable Innovation in the Textiles Industry

Marie Stenton [1], Joseph A. Houghton [2], Veronika Kapsali [1] and Richard S. Blackburn [2,*]

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Abstract: Humanity is currently facing a crisis of excess, with a growing population and the trend towards disposable goods, and the world's resources are under tremendous pressure. This is especially evident in the textiles industry, with increasing consumer numbers and the trend of 'fast fashion' causing demand to be at an all-time high, with non-renewable feedstocks depleting and production of natural fibres also under strain. Considering the future of textile production, it can be beneficial to investigate our past for inspiration towards more sustainable approaches. Much of the research into regenerated protein fibres was performed out of necessity during wartime, and while this demonstrates the potential for food waste to be exploited as a resource, the manufacturing methods used at the time now present issues for a circular economy due to the high amounts of toxic waste produced. Using a range of historical and modern literature sources, including journal articles, patents and conference papers, this review presents the historical precedent and research performed into *azlons*, regenerated fibres produced from waste protein-rich materials. Historical evidence shows that the success of these azlon fibres was short-lived, partly due to negative associations with deprivation and hardship, alongside the emergence of alternative man-made fibres, which were devoid of these connotations with never-before-seen physical properties. The social and political climate leading to the creation, and ultimate demise, of azlons is explored along with the influence of evolving technologies and the marketing of these textile products to consumers. Although the creation of products from waste is not a new concept, the literature has identified that the synergy between the challenges faced in a time of resource scarcity and the current trend of problematic excess reveals an exciting opportunity to learn from our past to create a greener future. Lessons that could help with the current crisis within the textile industry are extracted and presented within the concept of a circular textiles economy. Our findings show that there is notable potential for one regenerated protein fibre, made from casein extracted from milk waste, to be manufactured within a localised, circular economy in conjunction with the principles of green chemistry and sustainable textiles technology.

Keywords: regenerated fibres; regenerated protein fibres; waste; circular economy; valorisation; garment industry; man-made fibres; textile processing; textile history

1. Introduction

Global annual fibre production in 2017 was over 105 million tonnes (Mt) [1] with polyester (53.7 Mt) and cotton (25.8 Mt) making up 76% of the total; regenerated cellulosics (e.g., lyocell, viscose; 6.7 Mt), other plant fibres (e.g., linen, hemp; 5.6 Mt), polyamides (5.7 Mt), other synthetics including polypropylene (6 Mt), wool (1.2 Mt) and other natural fibres (0.4 Mt) make up the remainder. The garment industry produces an estimated 3.3 billion tonnes of CO_2e on an annual basis, based on 2017 estimates [2]. The uncontrolled release of microfibres (MFs) from both natural and synthetic fibres at different life cycle stages (processing, cleaning, washing) is a growing concern: plastic MFs account for over a third of all plastic reaching the open ocean [3] and are now pervasive in all ecosystems and potentially more damaging to biogeochemical processes, species and human health than other plastic waste; some recent studies show ~80% of ocean MFs are dyed/finished cellulosic fibres [4] whose impact is still not known. With apparel consumption set to rise from 62 million tons today to 102 million tons by 2030 (a 63% increase) [5], it is no surprise that we are in the midst of an ecological and environmental crisis; the needs to secure new sustainable approaches for the garment industry are identified as a matter of urgency.

The catastrophic environmental and ecological impact of plastics, including synthetic fibres, is well documented in the media. However, the impact of natural fibres such as cotton, silk and wool also have their impacts. For example, wool fibre production accounts for 36% of the total carbon footprint of fashion fibre production in the UK [6] proving that improvements in fibre production would have a significant impact on the overall ecological footprint of the UK's garment industry.

With growing public and consumer awareness, the environmental incentive for rethinking alternative material resources could not be more pertinent. Although some fashion brands are said to be making changes in their supply chain and opting for more environmentally friendly fibres, sustainable impacts resulting from efforts in the fashion sector are difficult to measure. Today, it is not uncommon for brands to promote an 'eco' range via switching to the use of more purported sustainable fibres or manufacturing processes. Yet, few offer sufficient insight to prove their claims and can be accused of 'greenwashing', the act of using misleading marketing strategies to persuade customers that a product is environmentally friendly. As for the determination of genuine sustainable raw materials, this can be difficult for brands and consumers alike due to a lack of legislation or clear guidelines as to what constitutes as 'sustainable' [7].

The implementation of circular design principles could offer a solution to this conundrum. A circular economy is an industrial system that is regenerative by design, with the end of one products lifetime becoming the beginning of another's [8]. In a circular economy, waste can be eliminated by shifting towards the use of renewable energy, ending the use of toxic chemicals and through the design of new materials, products and systems [9]. One of the core concepts of circular design is that waste can act as a feedstock, removing the end-of-life concept by transforming old products into new ones. In the context of regenerated fibres, especially regenerated protein fibres (RPFs) that were historically known as *azlons*, this waste is often organic in nature and poses an interesting opportunity.

The use of food production waste offers a huge opportunity with benefits to the environment and the UK economy. According to 2013 data, up to 2bn tonnes *p.a.* of all food produced in the world ends up as waste [10,11], a carbon footprint of 3.3bn tonnes CO_2e, ca. 8% of global greenhouse gas (GHG) emissions. Yet this waste is often unavoidable by-products that offer an exploitation opportunity, irrespective of the efficiencies of food production, with some notable examples that could be used for RPFs. A 2020 report by WRAP [12] highlights that the UK dairy industry produces ~14bn litres of milk *p.a.*, with ~555,000 tonnes *p.a.* of waste from production, which is either incinerated or spread on land; the chief by-product of cheese-making is whey (~228,000 tonnes *p.a.*), which contains a significant amount of casein. 82% of milk protein is casein with the remainder being comprised of whey; whey is already utilised in the dietary supplement industry, but the uses for casein are fewer, hence casein from food waste presents an attractive opportunity for valorisation, potentially for RPFs. Several other waste protein sources offer interesting resource potential for RPFs: World peanut production for edible oil generates 5.8 Mt *p.a.* of 'cake' by-product after oil extraction (2012 data [13]), which has a protein content of ~50%; over 885 Mt *p.a.* corn (maize) is produced (2013 data [11]), of which 25% is used for ethanol production, the major by-product of which is protein (~40% zein) [14]; and over 262 Mt *p.a.* soybeans are produced (2013 data [11]), processing of which generates ~12.7 Mt *p.a.* of by-product (known as okara) [15], of which the dry weight is 27.4% protein [16].

With the amount of waste being produced along with the advent of 'fast fashion' and other consumerism movements, the modern world is struggling with excess; this means that more research is going into what can be done with such waste. While most of this research investigates the future, it can be beneficial to investigate our past. Other times of struggle, albeit for a vastly different reasons, were during the two World Wars; the issue then was not one of excess, but rather one of limited availability of resources. The approach taken at the time, however, was similar and utilised waste as a feedstock to alleviate pressures on resources that were strained by military demand or simply unavailable due to the challenges of wartime trade. Textiles were especially important, with wool for uniforms being quoted as just as important as bullets during wartime [17]. Research and development during this period allowed for the creation of textiles from waste protein, but due to a variety of factors these RPFs were quickly forgotten once the wars had ended. The reasons for this and the lessons we could learn from our past for future development of sustainable fibres are explored within this review.

2. Methods

A review of literature from current and archive-based journal articles and patents has been applied to create a timeline, plotting protein-based fibre technological innovations against key social, technological, and political events around the globe (Figure 1). The concept of Thompson's *Rubbish Theory* [18] is considered to help understand the evolution of RPFs from a cultural and social perspective. Brooks and Rose [19] explore *Rubbish Theory* as a useful model for realising changing attitudes towards artefacts and to gain insight into why these fibres, once available across the globe, have disappeared. *Rubbish Theory* also traces shifting attitudes to the value of objects 'The relationship between status, the possession of objects, and the ability to discard objects' [18]. This framework enables a systematic understanding that an item's worth is not fixed but fluctuates over time. Thompson dissects these characteristics into three categories: Transient ('here today, gone tomorrow'), durable ('a joy forever') and rubbish; this theory also explores the dynamics through which rubbish can re-enter circulation as a valued commodity, potentially exceeding its original value [18]. In terms of a contemporary fashion market, this regeneration of value supports a circular economy of goods including textile fibres through recycling and reuse.

As we seek to understand the rise and fall of these fibres, it is necessary to investigate the relevant influencing factors: (1) The socio-political landscape of the time; (2) advances in technology; and (3) the way in which each fibre was marketed and presented to consumers. Through her own historical investigation, Brooks [20] also identifies three possible generations of RPFs, each developed in response to varying economic, political and social factors. The first were created between the mid-19th century and early 20th century, the second in the mid-20th century, and the third in the late 20th and early 21st centuries. Building upon this concept, a fourth generation will be identified to focus on fibres created in the 21st century and analyse the potential for a new range of fibres, created in response to excessive consumption over economic hardship.

This review seeks to understand the potential for protein by-products from the food industry, especially casein, as raw materials for the UK garment industry within the framework of a circular economy. Historical learnings have been combined with the outcomes of Brooks' framework, from the lens of a contemporary fashion market. Socio-political drivers influencing the journey of casein fibre technology are analysed to underpin the potential for a review of milk waste streams, as an approach to a circular strategy, therefore the literature has been reviewed with the circular economy and sustainability in mind. Approaching this historical research with a modern sustainability mindset allows an exciting opportunity to learn from the past while also utilising the knowledge and experience afforded from a modern perspective.

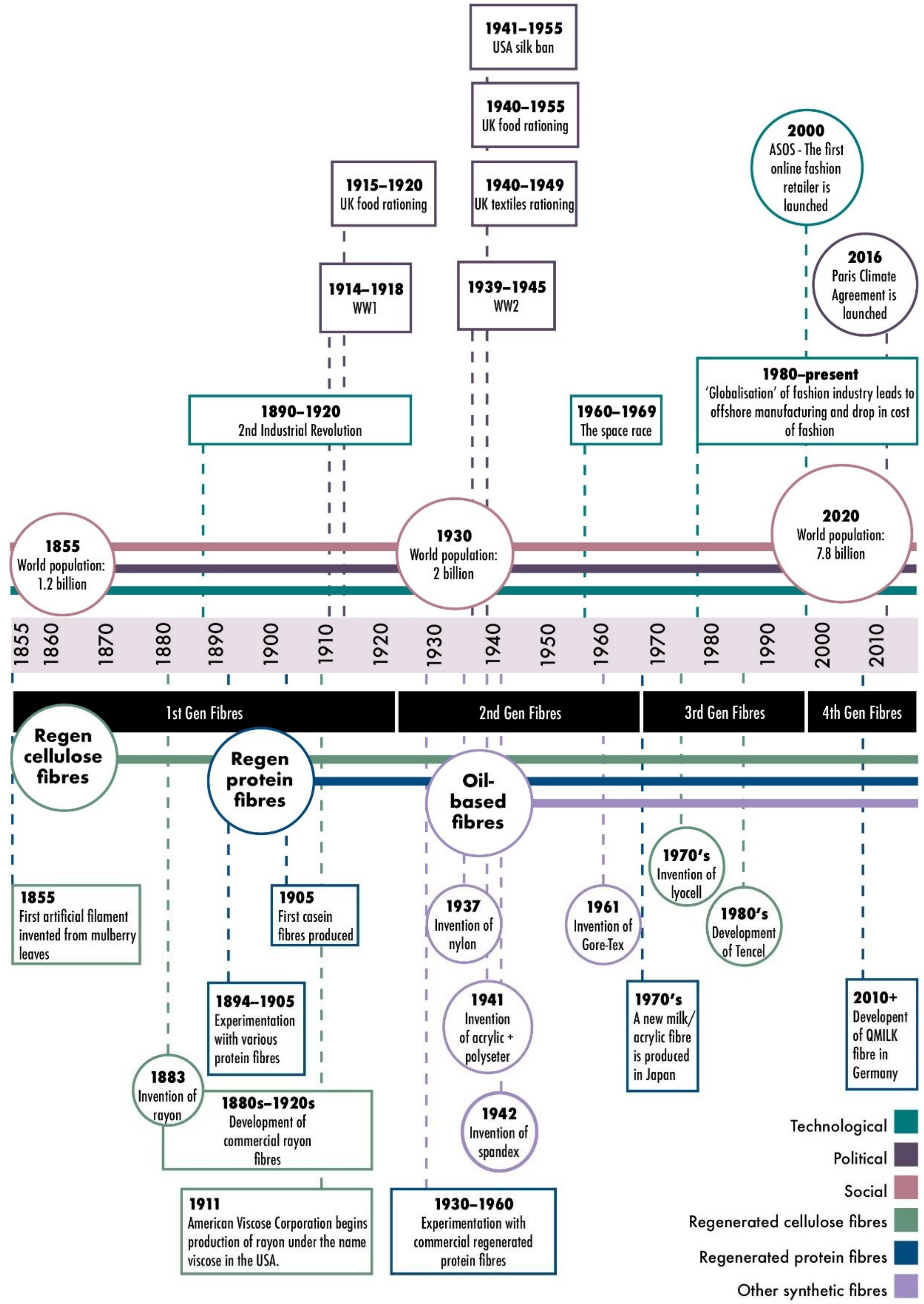

Figure 1. This timeline indicates the crucial events that might have influenced our fashion consumption choices, as well as demonstrating the shift in interest between three groups of synthetic fibres, from the first known man-made fibre in 1855, to present day.

3. Results

3.1. First Generation Fibres: 1855–1925

3.1.1. Socio-Political Context

The industrial revolution, the First World War (WW1) and the wider impact of globalization had significant effects on the development of RPFs. During WW1, many household products (from food to textile items) were replaced with substitutes known as 'ersatz', a term borrowed from the German language and often referred to because of the privations of war which came into prominence during WW1, with a resurgence in use due to the development of new, substitute products during the Second World War (WW2). Unlike regenerated cellulose fibres (notably viscose), which were invented some 25 years before WW1, RPFs were initially (and rather unsuccessfully) created as ersatz around the time of WW1. These initial fibres suffered from exceedingly poor strength and never reached the level of development needed to make them suitable for a commercial market, and by the 1920s industrial efforts had been largely abandoned.

3.1.2. Technology

The technology of natural fibres dates to pre-historic times where humans began to process biological materials such as animal skins to create garments and other textile products. Although the origin of man-made fibres as a concept is unclear, the link between observations of the silkworm's method of producing silk with the concept for manufactured fibres can be found in Hooke's *Micrographia* [21] where he describes the possibility of producing an "artificial glutinous composition" resembling the substance produced by the silkworm, which might be "drawn out into small wires for use".

The original patent describing a manufactured fibre was filed by Swiss chemist, Georges Audemars [22] who discovered a process for creating artificial silk using cellulose derived from the wood of the mulberry tree. Thirty years later, Sir Joseph Swan discovered a more efficient process of producing an artificial thread while experimenting with the incandescent electric filament lamp. Swan invented a device for extruding fibres and describes a deoxidising agent that prevented the fibres from burning explosively [23]; in this process, a solution of nitrocellulose was dissolved in acetic acid and forced through small holes into alcohol, which carbonised and set the resulting filaments. This method paved the way for French industrial chemist Hilaire Berniguard Chardonnet, who was the first to exploit the fibre for textile purposes, dominating the production of rayon for years to come [24].

Although early rayon was discovered in the 1880s, it was not until 1903 that a commercial way of making these filaments was discovered [25]. In 1905, British silk firm Samuel Courtauld & Company began manufacturing the fibre commercially, which then became known as viscose rayon, the term deriving from the viscous solution that comprised the spinning dope [26]. Soon after, the American Viscose Corporation began production in the USA. Many chemists across the globe used variations of this process to create their own versions of rayon, yet many were deemed unsafe for commercial production due to flammability and the use of toxic chemicals. In 1891, Chardonnet began production of an early type of rayon and the first commercially available man-made fibre, known as Chardonnet silk [27].

Although RPFs were invented in the 1890s, the vast majority of the 146 patents for producing fibres from protein sources were filed in the 1930s and 1940s [28]. The first on record is Adam Millar's 1894 patent of a gelatine filament, produced by forcing a concentrated, hot gelatine solution through nozzles to form fine threads. These were supported by a series of traveling revolving cylinders used to wind the threads before leaving them to dry for weaving. These threads were known as vanduara silk and were highly promoted at the time, despite being unsuitable for commercial use due to their poor strength and water absorption [25].

Casein fibres were amongst the most successful RPFs despite their common issues of low tenacity and wet strength. Five years after patenting his gelatine threads, Millar produced a 'proteids'-based fibre from egg albumen, blood albumen, vegetable albumen and casein [29]. This patent would largely inform the process for making casein fibres, patented by Todtenhaupt in the early 1900s [30] as a substitute for artificial silk and horsehair until his production company, Deutsche Kunstseidenfabrik, shut down [31].

3.1.3. Marketing

Major journals published statements regarding the threat of being burned by wearing rayon along with claims that it could dissolve in rainwater [32]. In 1905, The Textile Mercury described rayon to be 'stiff and wiry' and difficult to care for. Serious complaints were also being made that work in rayon factories was having a negative effect on the operatives, as well as reports of 'dreadful smells coming from rayon works' [32]. Today, rayon has survived the test of time, but early consumers were reluctant to accept rayon as a fashionable textile—and marketing the new fibre took large amounts of time and money. A 1930s report from the Women's Trade Union League of America reported that the use of carbon disulphide in the early manufacturing of rayon led to factory workers being poisoned, resulting in cases of carbon disulphate psychosis [33]; symptoms include skin burns and irritation, digestive issues, paralysis, pernicious anaemia and states of psychosis.

Unlike the persistent complaints of factory workers and the concerning articles written in home and textile magazines surrounding the dangers of rayon, there is little evidence to suggest that customers or workers were affected in such ways by RPFs. Although, first-generation RPFs were still under development and not yet suitable for any commercial market, and no promotional materials can be found. Rayon, however, was entering its first stage of commercial availability and appeared both under scrutiny and admiration by the press. Despite its faltering quality and safety concerns, some advertisers were quick to praise this new artificial fibre.

This early battle between chemists to create the first successful synthetic fibre, paved the way for larger companies such as the American Viscose Corporation and DuPont to form and play a large part in the commercialisation of man-made materials for years to come. By 1911 when the American Viscose Corporation had begun large-scale manufacturing of rayon (under the name viscose), RPFs were still in their infancy and needed much further work. During the start of the second generation of fibres, this development would pick up once again and RPFs were soon to become the unsung heroes of WW2.

3.2. Second Generation Fibres: 1925–1970

3.2.1. Socio-Political Context

During WW2, roughly 65% of the productive capacity of the textile industry was estimated to be on government fabrics [34]. As petrochemical-based synthetics had yet to reach a domestic textiles market, wool was used for uniforms and equipment, leaving mass shortages for civilian textiles. On top of this, fibres available for domestic textiles were of overall lower quality. In 1944, a survey undertaken by the Bureau of Human Nutrition and Home Economics discussed 'how essential fabrics were downgraded during the war' [35], which consequently had a positive impact in terms of encouraging innovation in fibre development. American and European manufacturers also feared that supplies of imported wool might become unavailable, which led to a race between countries trying to make their own technical progress in the production of alternative fibres, with the aim of creating a self-supporting textile industry [36]. RPFs were used to ease the substitution of natural fibres at this time of textile shortages and localisation. A range of home and fashion magazines would often promote them as wonder fibres, claiming that to accept them would help with the war effort; an editorial in the American fashion magazine Harper's Bazaar shows how these concerns were used to market the new fibres as a patriotic purchase: 'Now we will wear milk—dress in new milk-fed clothes based on discoveries that are rocking the fabric industry and taking the sting out of wool shortages' [37].

During the development of RPFs, many different sources of protein were explored depending on what the country of origin had a surplus of. The US explored RPFs from

soy protein and used zein (from corn waste) to produce the fibre *Vicara*; the UK evaluated peanut waste due to large amounts of peanuts being imported from the British Empire. Italy, however, proved to be the leader in RPFs before, during and after WW2; with their pedigree in the textile industry and the political and cultural climate within the country during this time, Italy became the world leader in RPFs, and indeed regenerated fibres in general. Italy was of particular interest in the context of RPFs with *Lanital*/*Merinova* fibre being adopted by the Italian fascist party to represent the country's independence and superiority in the textile world. Italy's obsession with RPFs was ignited by the advent of the Italian futurism movement, which started in 1909, and called for all areas of the arts to disregard the old and focus on new and exciting innovations. Fashion was no exception with new, innovative clothing being made from unconventional materials including glass, aluminium, rubber, paper and, of course, milk. Italy also led the way in the development of rayon and became the world's largest producer of the regenerated cellulose fibre in 1929, with the company SNIA Viscosa being the largest manufacturer. By 1935, the company was also producing the milk fibre *Lanital* (Figure 2), which was heralded by Mussolini as a key breakthrough, with 3.7 kg of fibre produced per 100 kg of waste milk [38].

Figure 2. (**Left**) Italian fascist party flag made from *Lanital*; (**Right**) SNIA Viscosa advertising for *Sniafiocco* (viscose) and RPF *Lanital* ('I tessili dell'Indipendenza', translation: 'The textiles of Independence').

3.2.2. Technology

The Italian government was keen on promoting *Lanital* on a global market, with patents being filed in multiple countries including the US where *Lanital* was produced under the name *Aralac*. This had a brief popularity in the high-end fashion market, before the advent of WW2 turned the use of *Aralac* into a substitute fibre, where its lack of tensile strength, especially when wet, led to a decrease in its popularity and eventually to the stopping of production in the US by 1948. SNIA Viscosa kept manufacturing *Lanital*, but under the name *Merinova* [39], until the mid-1960s, despite its popularity taking a severe hit after WW2 during which its mechanical shortcomings were shown during its use in the Italian military's uniforms (1944).

The technology used to produce RPFs changed rapidly during WW2, affording production of fibres to replace wool. Many of the changes aimed to improve the functional properties of the fibres, as opposed to making the manufacturing process more efficient. The number of patents filed over time by researchers and manufacturers seeking to improve poor overall wet strength of RPFs indicates that this was a persistent problem. Table 1 shows a comparison of tensile properties of different RPFs compared to common textile fibres, where it is observed that dry tensile properties are comparable with wool, but a 40–80% reduction in strength is observed when RPFs are wet.

Table 1. Tensile strength of regenerated protein fibres and conventional textile fibres [40].

Fibre	Tensile Strength (MPa)	
	Dry	Wet
RPF from casein	126	40
RPF from peanut	115	34
RPF from zein	115	69
RPF from soybean	69	14
wool	184	126
cotton	413	459
PET	608	608

Looming technical issues and a rise in raw materials and production costs were met with the launch of petrochemical synthetic fibres including nylon, polyester and acrylic. These new synthetics provided a more consistent supply of materials and offered superior performance over RPFs (and other natural fibres) contributing to their downfall in the 1950s [41]. RPFs were closely guarded, mainly due to the fibres lack of success, and by 1955 the total output of protein fibres was well below half that of synthetics [42]. Not only had a new range of fibres taken over the factories, advances in crease-resist finishing of rayon, combined with improvements in its wet and dry strength, pushed rayon further ahead of RPFs in both industry and consumer opinions [32]. In the US, production of cellulosic fibres increased from nearly 16,000 tonnes in 1923 to nearly 6 Mt in 1951. In comparison, the output of all other man-made non-cellulosic fibres was roughly 95,000 tonnes [36].

After the war, the reputation of these abandoned fibres plummeted rapidly, and the industry had to consider whether adjustments to quality and cost could present it as a desirable fibre for commercial use [43]. Conversely, a new range of synthetic fibres had come into light and thrived in areas where RPFs had failed time and time again; they were cheaper to manufacture and far superior in terms of strength, durability and ease of care. Manufacturers began to question whether their efforts were worth it and the production of RPFs slowed to a halt. Brooks and Rose [19] believe that by this stage the changing status of RPFs fits the cycle of *Rubbish Theory* closely. WW2 ended in 1945, but textile rationing continued until 1949. Towards the end of the 1940s RPFs became perceived as inferior, substitute fibres associated with deprivation and hardship; 'new' synthetics (nylon, polyester and acrylic), on the other hand, were advertised as the textiles of a care-free, modern world, demonstrating their cultural value.

The period between 1914 and 1920 created a great expansion in the viscose rayon industry. Like the shortages of WW2, a lack of natural raw materials during WW1 led to extensive research and experimentation on artificial textiles placing viscose fibres in a 'durable' position [32]. Into the 1950s, synthetic fibres including rayon, polyester and nylon had been transformed from an expensive and luxurious novelty into a cheap and useful product; within 20 years synthetics would rival even established natural fibres in strength and popularity [36].

After reviewing the typical manufacturing process for casein-based fibres during the 1940s, it is evident that a range of undesirable and potentially harmful chemicals were employed throughout production. One of the most notable chemicals used to produce casein fibres at the time was formaldehyde (CH_2O) [44], which was used primarily as a crosslinking agent, creating bonds between the protein polymers within the fibre to increase both dry and wet tensile strength. Today, the safety issues around formaldehyde are much better known, with acute toxicity, suspected carcinogenicity and mutagenicity meaning that its use, and disposal, are subject to far more regulations [45]. Alongside formaldehyde,

high concentrations of sulphuric acid were used in the coagulation and hardening baths, and this would have resulted in problematic waste treatment or challenging regeneration of the acid medium along with issues regarding health and safety or workers and challenges in designing equipment capable of withstanding the acidic medium. High concentrations of salts (commonly aluminium or sodium salts) were used in both the coagulation and hardening baths to cause fibre shrinkage, which assists in aligning the protein molecules within the fibre and help prevent the fibres from sticking together within the spinning process [46]. While there is no recorded complaint of the use of these chemicals in the production of casein fibres, the use of concentrated acidic salt medium, combined with the use of formaldehyde throughout the production process would likely have posed more issues involving worker safety and environmental damage if the fibres had reached their full potential and were produced on a mass scale.

3.2.3. Marketing

Despite the quality of RPFs produced, efforts were put into their promotion and advertisers were likely to put a positive spin on their properties. This was especially the case after the war when their popularity was in decline and can be attributed to the initial expenditure that was put in by companies and governments. In 1945, The UK government invested £2.1 million to produce a new factory in Dumfries [47] for their RPF *Ardil* manufactured from waste peanuts, shortly after a marketing campaign was launched in effort to increase product popularity (Figure 3, left). Indeed, even Henry Ford attempted to increase the popularity of RPFs; the Ford motor company pushed for the inclusion of soy protein fabrics in their cars through research at the United States Soybean Laboratory and produced a patent detailing their work [48]—Ford even went so far as to model a soy-protein suit (Figure 3, right), although it was said to have been itchy and uncomfortable to wear. As with other RPFs, the end of WW2 in 1954, along with the accompanying reduction in international wool prices due to ease of trade, led to a loss of interest in soy fibres [40].

Figure 3. (**Left**) An example of advertising for Ardil with the tag line 'Happy families—with Ardil ca. 1995; (**Right**) Henry Ford modelling a suit made of soy protein fibres circa 1941.

Once seen as the wonder fibres that helped fight the war, today few examples of RPFs remain in museum archives or textbooks. Brooks and Rose [19] believe this to be an intentional decision driven by the understanding that such were no longer of government interest and therefore would be needless to retain records of a failed project. On the other hand, rayon, polyester, acrylic and nylon were making their mark worldwide, overtaking natural fibres in popularity. This second generation of fibres, best known for its innovation in difficult times, made possibly the most lasting and important contributions to the history of the textile industry. Today, these fibres are still widely used in all manner of textile items, making it difficult to imagine a world without them.

3.3. Third Generation Fibres: 1970–2000

3.3.1. Socio-Political Context

By 1970, the global population had reached 3.7 billion, a 2.6% increase from the previous decade and one of the fastest growing generations in history [49]. As population increased, with it came the increase in production of commodities, putting strain on non-renewable and renewable resources alike. Over several decades, globalisation of the fashion industry played a huge part in how we make and buy clothes, and offshore manufacturing meant that clothing could be produced faster, at lower quality and at a fraction of the price. This led to the birth of 'fast fashion', a linear business model encouraging over-consumption and generating excessive waste [50]. In 1976, the market for rayon fibre was poor, with plants operating at less than 45% capacity; the cost of cotton and polyester had fallen dramatically, whilst rayon prices continued to rise [51].

As growth of all kinds was increasing, a new group of environmentally aware consumers and businesses was beginning to form. Due to the rise in global communication and offshore manufacturing, concerns were raised surrounding unethical practices such as child labour and low wages. When, in the mid-20th century, eco-consciousness was reawakened in developed countries, such issues were largely ignored within the fashion and textile industries.

Falling within the concept of *Rubbish Theory*, McLeod [52] claims that environmentalism comes in waves, falling in and out of fashion over time. Aside from a brief uptake in environmental concern in the 1960s, there was little significant activity regarding the environmental impact of textile manufacturing until the 1980s and 1990s when the signpost for the eco-fashion movement was launched with Esprit's Ecollection in November 1991 [53]. This collection was said to be revolutionary for its time and used a range of *Tencel* (regenerated cellulosic) fibres, organic and unbleached cotton, natural dyes and naturally coloured wools. They also used a carefully selected range of synthetic dyes that were free of heavy metals, achieved 75% less dyestuff in effluent, and used significantly less water and energy. Fabrics were mechanically pre-shrunk to avoid the use of resins and formaldehyde and biodegradable enzyme washes were developed to smooth fabrics and prevent pilling [54].

3.3.2. Technology

After a second dip in interest in RPFs, innovations in biotechnology and demand for more sustainable fibres sparked a flurry of activity in the late 20th century [20]. This combination of new technology and demand for fibres with a reduced ecological footprint meant that textile developers where once again looking to alternative sources for raw materials and advanced manufacturing methods. The milk/acrylic blended fibre *Chinon* was produced in 1970s Japan but is said to have been very expensive and quickly ceased production [55]. Interest lay primarily with milk and soybeans as a protein source, although chicken feathers were also said to have been researched. These new fibres aimed to exploit the soft hand and lustre of the protein while adding strength and durability by adding a synthetic resin and were also claimed to have an ecological benefit. Soybean fibres primarily became a substitute for cashmere, reducing the number of grazing cashmere goats and thus helping to minimise desertification in China [56]. This new generation of bioengineered fibres claimed to have biological health care functions and natural, long-lasting antibacterial effects, gaining international ecological textile certification. They were described as hygienic, flexible, smooth, sheen, renewable, biodegradable and eco–friendly, but with low durability and still very expensive [57].

Also driven by environmental concerns, a new regenerated cellulosic fibre lyocell (US/UK brand name *Tencel*) was developed in 1972 by a team at the American Enka fibres facility, before being commercialized by Courtaulds Fibers in the 1980s. Lyocell was developed and marketed as a sustainable alternative to viscose. Viscose is manufactured by soaking cellulose pulp in sodium hydroxide (NaOH) to produce alkali cellulose, followed by aging for 2 to 3 days, then mixing with liquid carbon disulphide (CS_2) to produce sodium cellulose xanthogenate, which is subsequently dissolved in alkali and used in a wet-spinning process, where the cellulose solution is precipitated as pure cellulose fibres in an acid coagulation bath [26,58]. However, CS_2 is hazardous [59], expensive and has a negative environmental impact [60]. In contrast, lyocell fibres are cellulosic fibres that are produced by regenerating cellulose into fibre form out of a solution in *N*-methylmorpholine-*N*-oxide (NMMO) hydrate [61], and have excellent environmental credentials [62,63]; the main environmental advantage to using NMMO is that it is easier to recapture, creating a closed-loop process where the chemicals are re-used rather than being disposed of with, typically, 98% of the solvent recovered [64].

Another European company involved in the production of lyocell fibre is Lenzing AG in Austria. Originally involved in the manufacture of viscose rayon, Lenzing established its first lyocell plant in 1990, and a full-scale production plant in 1997 running at a capacity of 12,000 tonnes *p.a.* of lyocell staple fibre, branded as *Lenzing Lyocell*. After acquiring the Tencel Group in 2004, in 2021 Lenzing is the world's largest lyocell fibre manufacturer, capable of supplying 130,000 tonnes *p.a.* for the global market [65].

3.3.3. Marketing

Marketing of green and sustainable textiles and clothing increased, however issues regarding the legitimacy of these claims must also be considered. Coined by environmentalist Jay Westervelt in 1986, the term 'greenwashing' refers to companies posing as sustainable through vague 'eco-friendly' policies and campaigns [66]. Another challenge regarding promoting behavioural changes towards and within the fashion industry was (and still is) the overall narrow understanding currently held by both the public and industry about what 'sustainable fashion' actually means. This inevitably makes it easier for companies to use words such as 'green', 'organic' or 'clean' with little questioning from consumers or stakeholders, and there is no consistent international standard that quantifies any of these terms.

Though there are many ways to achieve sustainability, what appears to be most readily promoted by brands with a desire to appear 'green' includes the use of naturally derived and organically produced raw materials. As discussed by Dempsey [67], 'While important, these efforts only touch the surface of a much deeper set of solutions, and in the case of material efficiencies, they can sometimes produce a paradoxical effect'. This is because the issue is not a single-faceted problem and therefore requires a multidimensional approach. Though feedstock for materials is of course a major issue, with many man-made polymers being derived from non-renewable resources such as crude oil, this is only one side of the issue. Manufacturing methods, efficiency, waste production and a host of other issues play into this as well. The matter of demand must also to be considered; swapping all the world's textile needs to natural resources such as cotton would put huge amounts of strain on the production of such natural resources and would likely lead to further issues centred around the need to produce vast amounts of a single resource. This can be clearly seen in the case of cashmere: Research has been done that indicates that the increased production due to demand of cashmere is leading to desertification in Mongolia [68,69] and a life cycle assessment performed on silk production in Southern India indicates that the environmental impacts of this production process are higher than that of other natural fibres [70].

Unlike in the second generation of RPFs which saw huge levels of investment and government backing, new RPFs in the third generation were not as widely promoted. As many fashion campaigns moved away from quality, and advertisements became more focused on price and garment aesthetics over fibre and functionality. As brands pushed more styles and more collections per year and relied on existing, oil-based fibres such as polyester and nylon, a dependency on cheap and low-quality fibres meant that consumer education in terms of fibres was not a priority. As the fast fashion market increased, the domestic textiles market decreased dramatically, and consumers started to know (and potentially care) less about the origins of their garments.

Although environmental preservation and sustainability was a rising topic of importance for some, the third generation of fibres appears to sit in an era of complacency. Following the innovation of the second generation, use of the most successful fibres was in full swing and there was little reason to explore or invest outside of these textile staples. In terms of priorities, increased speed, and reductions in the cost of manufacturing took precedence over quality. Based on this new economy, the third generation introduces us to the first fast fashion powerhouses and ultimately leads us into our fourth and final generation of RPFs.

3.4. Fourth Generation Fibres: 2000–2021+

3.4.1. Socio-Political Context

Twenty years into the rise of fast fashion, the first dedicated online fashion retailer, ASOS, allowed us to shop from anywhere in the world, at any time of day or night. As a result, the fashion industry opened up to a variety of new styles, influences and even faster production. The rise of mobile shopping and social media increased the pace once again [71], paving the way for even cheaper retailers such as Misguided and Boohoo. It could be argued that we have now passed 'fast fashion' and are in a new generation of 'hyper speed fashion,' with little intention of slowing down.

At the turn of the new millennium, an emergence of natural disasters and economic crises pushed us to question the integrity of businesses and create a demand for greater transparency in the age of online communication [72]. The year 2020 alone has seen a series of devastating climate disasters around the world such as the Australian wildfires, drought in east Africa and flooding in south-east Asia. Events such as these force over 20 million people a year from their homes, not to mention the loss of lives. In the past 30 years, the number of climate related disasters has tripled and The United Nations Environment Programme estimates that adapting to climate change and coping with damages will cost developing countries $140–300 billion *p.a.* by 2030 [73]. Furthermore, we are currently facing the largest pandemic of the modern world, Covid-19, potentially caused by civilisations' impact on nature and biodiversity. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) states that our actions have "impacted more than three quarters of the Earth's land surface, destroyed more than 85% of wetlands, and dedicated more than a third of all land and almost 75% of available freshwater to crops and livestock production . . . This rampant deforestation, uncontrolled expansion of agriculture, intensive farming, mining and infrastructure development, as well as the exploitation of wild species have created a 'perfect storm' for the spill over of diseases from wildlife to people" [74]. IPBES predicts that future pandemics are likely to happen more frequently with greater economic impact and causing more deaths if we are not extremely careful about our impeding choices.

In 2017, 105 million tonnes (Mt) of fibre were produced globally [1], representing a ten-fold increase since 1950, with 62% of this being petrochemical-based fibres. The amount of clothing bought *per capita* in the EU has increased by 40% in the last few decades [75], and with global population set to increase by 40% by 2050, the environmental impact of the textile industry is set to increase rapidly accordingly [76]. In the first decade of the 21st century, a growing number of initiatives were developed by governments, trade unions, campaign groups and fashion brands, to tackle major environmental, social and economic sustainability issues [72]. The Changing Markets Foundation also held brands including Zara, H&M and ASOS accountable for using highly polluting viscose factories in China, India and Indonesia [77]; together, these countries account for over 83% of global viscose

fibre production. At production plants in China, investigators found evidence of water and air pollution, worker fatalities, and severe health impacts on local residents [78]; production of natural fibres including viscose also contributes to deforestation (including the depletion of endangered and ancient forests) and loss of biodiversity and animal habitats. The fashion industry is projected to use 35% more land for fibre production by 2030, an extra 115 million hectares that could be used to preserve forests to store carbon or grow crops for an increasing population [5]. This choice to produce a material object rather than produce food links into the 'food versus fuel' debate and leads to a potential new 'food versus fashion' issue if this trend continues.

Outside of the fashion industry, initiatives such as the Kyoto Protocol and the Paris Climate Agreement were put in place to reduce GHG emissions, a clear sign of a global recognition of the environmental destruction caused by industrialisation over the decades. Despite this positive step, there has been criticism surrounding the effectiveness of the regulations, claiming that they are not enough to keep global warming below 2 °C [79]. A total of 192 countries signed the Kyoto Protocol, yet by 2005 CO_2 emissions were still on the rise, and by 2009 global emissions had risen 40% since 1990.

The current trend of fast fashion is beginning to be challenged by both public perceptions; with more people demanding traceability and sustainability in their products, and by legislative and political agendas; with more legislation being put in place to reduce emissions, increase safety, reduce waste production and limit deforestation. This cultural shift will become increasingly evident in the coming years and allows a unique opportunity for novel research into new and innovative textiles to be performed, not only focussing on a fibre's properties and ease of manufacture, but also incorporating circular economy and sustainability principles into its design. RPFs fit into this niche with their feedstock reducing current waste stream volumes while also potentially alleviating the pressure on current textile manufacturing. The challenge will be incorporating more green synthesis principles into the production of these fibres, and the area of green chemistry and sustainability has come far since invention of first and second generation RPFs and with it the opportunity to take the research done by those early pioneers and refine it with modern knowledge.

3.4.2. Technology

Although lower than other synthetic fibres and some natural fibres, the impact of some modern, regenerated cellulose fibres is still relatively high, notably some viscose that uses wood sourced using poorly managed forestry practices, energy, water and chemically intensive processes, which also have dramatic health implications on workers, local communities and the environment [80]. The fact that some regenerated cellulose fibres have excellent sustainability credentials (e.g., lyocell, sustainable viscose) and some are severely problematic does not help the general lack of understanding in the consumer population as to what sustainability truly means—how does one easily select a sustainable viscose garment? Education into the multi-faceted nature of sustainability including all the steps within the process from feedstock, to process efficiency, to waste generation and end of life will continue to improve and with it a more discerning consumer base that demands that its products be truly sustainable. Today, around 8000 different synthetic chemicals are used in the textile industry to turn raw materials into final products [81], the dangers and health hazards associated with CS_2 in viscose production have been an issue for over 100 years.

Following a brief revival of RPFs in the 1970s, German company QMILK developed the process to produce a quality, organic textile fibre from milk waste in 2010. This fibre is manufactured through a resource efficient, zero-waste process using no chemical additives. The resulting biopolymer fibre offers the potential for numerous high-value applications and can be modified for a range of markets including fashion, home textiles, automotive, medical and cosmetics [82]. Although extensive development of both QMILK fibres and product ranges has been carried out, none are yet commercially available.

Aside from a resurgence in interest of RPFs, a new range of bio-based synthetic textiles created from agricultural waste is beginning to emerge. One example is *Orange Fiber*, an

Italian company creating sustainable fabrics from citrus juice by-products. Their fabrics are formed from a cellulose yarn that can blend with other materials and when used in its purest form, it is reported that the resulting 100% citrus-based textile features a lightweight, silky texture [83]. Another example is *Piñatex*, a nonwoven textile made from cellulose fibres extracted from waste pineapple leaves, polylactic acid, and petroleum-based resin to create a natural leather alternative, with application opportunities in fashion and accessories, soft interiors and automotive industries [84].

The material science company, Circular Systems, is a social purpose corporation using new regenerative technologies to manufacture innovative materials. Their 'waste to fibre' platforms, *Texloop* and *Agraloop*, offer solutions to agricultural waste streams and textile management. The Agraloop Bio-Refinery transforms food crop waste into high-value natural fibre products in a cost competitive and scalable way, providing sustainable and regenerative benefits. The system can utilize a range of feed stocks including oilseed hemp and oilseed flax straw as well as pineapple leaves, banana trunks and sugar cane bark [85].

3.4.3. Marketing

Given the heightened awareness of climate change and depletion of natural resources, since the new millennium, a growing consensus has emerged that over-consumption via faster and faster fashion cycles must end. Sustainability is no longer a passing trend in fashion and a new body of conscious consumer is emerging; with this being the case, it can be predicted that future marketing of sustainable textiles will see a large increase, and hopefully alongside better consumer education, include more evidence of sustainability and traceability. Unlike the lack of evidence to support new fibres throughout the third generation, new and innovative fibres are once again making an appearance in the mainstream media. Although many are still in their development phase, companies such as Circular Systems are investigating ways to collaborate with brands, manufacturers and providers of agricultural waste, starting with small, collaborative collections and leading towards large scale changes to the traditional supply chain. With consumers now demanding more information on the origins of their clothing, it is the perfect time for developers of fibres—as well as fashion—to promote their technologies direct to consumers as well as business to business.

The rise of online journalism, as well as brands/manufacturers/developers having the ability to create their own websites and tell their own stories, allows businesses and consumers alike to seek further information and compare new technologies and fibres. Unlike the second generation of RPFs, where much innovation was funded by governments and happened behind the doors of large corporations (such as SNIA Viscosa and DuPont), much innovation is now crowdfunded or personally funded by small, independent start-ups. As competition in this sense is higher, the importance of transparency and having a more genuinely sustainable product to promote is greater than ever.

4. Discussion

Born from political crisis and material shortage, RPFs were once seen as the fibres of the future, yet, for the range of reasons discussed throughout this paper, were buried in the past. The modern climate of consumerism and fast fashion is providing a very different set of challenges involving excess and problematic waste generation. These challenges, while the antithesis of the original motivations for the development of RPFs, provide a similar opportunity for exploration into the synergy between reducing waste volumes while also alleviating the pressures of an increasing textile market.

First- and second-generation RPFs were plagued by issues regarding their properties, especially their wet tensile strength, but due to the demands of the time were still utilised as substitute fibres; the research performed into the development of these fibres was fast to make sure that the demands of wartime textile industry were met. After the end of hostilities, these fibres fell out of favour due to their lack of attractive mechanical properties and their association with substandard substituted materials, and after a brief push by

governing bodies to make use of the manufacturing sites invested in during wartime, these fibres were largely forgotten. Attempts have been made subsequently to research and even commercialise RPFs, however without the impetus of world-wide conflict to put pressure on the textile industry, these attempts were short-lived. Current trends towards a more sustainable and locally sourced economy have provided an interesting opportunity for RPFs to once again find their place in the textile world.

The area of biobased, biodegradable fibres from natural, renewable feedstock using green and sustainable methods is going to increase in importance if current trends continue. With fast fashion meaning that more clothing *per capita* is being purchased and with global population increasing, along with the increased awareness and concern over sustainability and traceability of commercial product, increasing impetus is going to be put on finding and developing novel methods for fibre production, while at the same time reducing excess waste created because of our expanding population, most notably in the food production industry. Creating products from waste is not a new concept but, differing from the direction taken during wartime in the 1940s, sustainability throughout the production of fibres will have to be a priority, utilising circular economy themes and considering the environmental and sustainability impact of everything, from the feedstock, to chemicals, energy and water usage and end of life for these fibres. The advancement in green and sustainable technology and chemistry gives opportunity to tackle the issue of producing truly sustainable RPFs fit for purpose for use in the textile industry.

Care would also have to be taken when considering the availability of the protein feedstock for textile products, which is especially important when waste (in this case from milk manufacture) could potentially be valorised back into the food industry. This poses environmental, societal and economic questions that must be analysed in depth to determine if the best routes for valorisation, in order to find a balance between valorisation for human nutrition or valorisation to reduce the environmental impact of 'fast fashion'. It may be that garment applications do not currently offer the best economic value for utilisation of milk waste compared to existing food products (e.g., animal feed, nutritional products); however, the unique properties casein fibres could potentially enable their use in high-value, non-apparel textile applications, such as medical textiles [86], which significantly changes the value proposition.

Localised industry was performed out of necessity during the World Wars, but modern trends are beginning to shift to a more localised economy, with the environmental impact of shipping products and feedstocks around the world no longer being ignored. Alongside this, unprecedented incidents such as the Covid-19 pandemic further highlight the benefits of self-sufficiency and utilisation of available local feedstocks. If, as the IPBES predicts, pandemics are going to occur increasingly in the future, locally sourced production would be beneficial from an environmental, economic and availability standpoint. Similarly, ethical and local sourcing of textiles and steering away from the typical outsourcing of production not only increases the ecological benefit of the textile, but also means that businesses have more control over production and worker welfare.

RPFs offer a unique opportunity to learn from our past for the betterment of our future, the needs of both past and future, although very different, potentially allow for the same solution. Production of fibres from waste is not a novel concept, but the production of fibres from waste protein sources has been largely forgotten. New research in this area utilising the advancements in technology and chemistry of the modern age is an exciting opportunity, and combined with the concept of a circular economy, a potential, truly sustainable textile fibre is possible.

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10.6.2 Paper 2: From Clothing Rations To Fast Fashion: Utilising Regenerated Protein Fibres to Alleviate Pressure On Mass Production

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Review

From Clothing Rations to Fast Fashion: Utilising Regenerated Protein Fibres to Alleviate Pressures on Mass Production

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Abstract: Sustainable methods of practice within the fashion and textile industry (FTI) often strive to employ a circular economy that aims to eliminate waste through the continual use of resources. Complex problems such as waste, consumption, and overproduction are heavily intertwined; the main aim of this paper is to report on research focused on re-examining the potential of food waste streams as a commercially viable and circular source of raw materials for the FTI. Herein, regenerated protein fibres (RPFs) from food production waste streams rich in protein have been chosen as the main topic of focus. RPFs have a rich and relevant history from a local manufacturing perspective during wartime and post-war clothing rationing (1941–1949) in the UK. RPFs were used to meet civilian needs for wool-based textiles as part of a wider series of 'make do and mend' strategies designed to manage the consumption of new textile products. However, RPFs demonstrated inferior quality in terms of durability when compared to wool-based textiles, a significant contributing factor to the consequent commercial phasing out of RPFs. In today's take–make–waste model, the FTI landscape can be defined by speed, from slow (high-quality materials and construction, long-lasting products) to fast (seasonal, disposable, low-quality materials and construction), the latter infamous for dire environmental impacts. A key objective of this research is to review the association of quality and longevity within the context of a local and circular fashion economy in which textile quality and lifecycle analysis are holistically matched to the longevity of the textile, garment, or product to reduce waste across the supply chain.

Keywords: waste; regenerated protein fibres; regenerated fibres; textiles; speedcycles; consumption; quality; circular economy; man-made fibres; textile history

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1. Introduction

The time needed to reverse the effects of climate change is quickly running out. This research brings together a necessary range of literary sources and disciplinary expertise to analyse the bigger picture surrounding the development and consumption of sustainable new materials and their impact upon the environment. Regenerated protein fibres (RPFs) have been chosen as a primary example due to the unexpected synergy between the modern climate of overproduction in the textile industry and the political crisis and material shortage experienced during the age in which RPFs, historically known as *azlons*, were developed. Together, these two issues provide a refreshing outlook for the exploration of reducing locally produced waste volumes while relieving pressure on natural and synthetic fibres through increases in production.

The fashion industry is responsible for 10% of worldwide GHG emissions, including 4% of global CO_2 emissions, and this is on-trend to increase to 25% of global GHG emissions by 2050 [1–3]. When compared to sectors that are typically considered heavily polluting, such as aviation and maritime shipping, the fashion industry exhibits a much larger GHG emission (10% as opposed to 4.4% for aviation and maritime shipping) [3]. Not only this, but a large proportion of the aviation and maritime shipping is devoted to moving textiles, raw materials for the production of textiles, and finished clothing articles around the world, increasing the carbon footprint of the fashion industry further. With the current growth of the fashion sector, it is predicted that freight use will as much as triple by 2040 [3]. The fashion industry is also one of the largest producers of wastewater in the world, contributing 20% of wastewater produced globally [2,4,5].

The burden of items from the fashion industry at the end of consumer use cannot be ignored, with 85% of all textiles ending up in landfills every year rather than being recycled or degraded back into the environment [3]. For the clothing market alone, this equates to USD 400 billion of clothing being wasted annually [6], which is being driven by a rapid increase in the production and consumption of textiles, with the textile industry doubling in the last 20 years and average global textile purchasing increasing from 7 to 13 kg/year per capita [7]. This average is heavily skewed towards the western world, with the USA purchasing 37 kg/capita/year, Australia 27 kg and Western Europe 22 kg, while Africa, India and Southern Asia exhibit an annual purchasing of just 5 kg/year per capita [8]. Taking Australia as an example, the average Australian purchases 27 kg of new textiles per year and discards an average of 23 kg to landfill within the same amount of time [9].

With fast fashion and a growing global population, along with increased concern over the sustainability and traceability of products, finding and developing novel methods for textile production whilst reducing excess waste is an ever more prevalent challenge [10]. Although feedstocks for materials is currently a major problem, the issue of demand must also be considered. Currently, petrochemical-derived fibre use is 62% of the global total, with cotton at 25% of this total [11]; phasing out petrochemical-based fibres entirely would put a huge strain on the production of natural resources and would likely lead to further issues centred around the farming of a single raw material, such as cotton. The processing of natural fibres also depends on non-renewable resources, requiring large amounts of chemicals and high use of thermal and electric energy [12,13].

A commonly accepted solution amongst the fashion industry is to 'slow' the fashion cycle and focus on the production of high-quality garments [14]. The interpretation of 'speed' in the fashion industry often relates to the 'use phase' of a product [15] (how long a product is designed to be used) or the 'production speed' (how quickly a product can be delivered from concept to store) [16]. It could be argued, however, that a mixed economy of both slow and fast fashion is necessary to creating an inclusive fashion system capable of reflecting the genuine needs of consumers and that a change in consumption habits and consumer mindsets is the key to the sustainable implementation of such a system. As stated by Kendall [17], "We're caught between two economies of time ... one fast and furious, the other slow and steady. Industry need not design what it makes to be durable beyond a certain amount of time, any more than nature does."

The concept of 'speedcycles' was initially developed through the Circular Design Speeds project as part of Mistra Future Fashion Design Theme research (2015–2019). The aim was to develop 'ultra-fast' and 'superslow' design prototypes for different circular fashion scenarios using collaborative and multidisciplinary research methods [18]. Although the design and manufacture of durable and long-lasting clothing have historically been a priority of the fashion industry, the concept of slow fashion has been promoted in recent years as a new alternative to fast fashion. However, as discussed by Goldsworthy [16], the problem with only focusing on a slow speedcycle is that without a shift in both cultural attitudes and garment collection schemes, many of these items will still end up in landfills without fulfilling their full potential. Such concepts, while admirable in their efforts, may reduce focus to only part of the system and are too simplistic to solve the larger issues at hand. There is also a range of socio-economic limitations to the switch to a completely slow fashion market, which tends to be less affordable and may be unattainable to a range of consumer demographics.

The creation of RPFs from food industry waste could offer a new perspective to our interpretation of fast and slow speedcycles through the design of textile materials that require a low input of resources and are created to last a specified amount of time. Drawing inspiration from the textiles market during wartime, this paper explores the necessary means to alleviating pressures on mass consumption whilst still offering an ethical and 'affordable' fast fashion model alongside a slow fashion model. This research also aims to identify any gaps in both the historical and contemporary data surrounding the production of RPFs from a sustainability viewpoint, thus outlining opportunities for further investigation.

2. Methods

This paper is based on a literature review interconnecting design, science, and industry to explore how textile materials can be created from food industry waste to help tackle complex problems such as waste and overconsumption in the fashion industry. The authors used regenerated protein fibres (RPFs) as a case study to compare how the approach taken to feedstock shortages during the world wars could be analogous with these more contemporary issues. The research question is to explore how RPFs from food industry waste offer a new perspective on our interpretation of fast and slow speedcycles whilst alleviating pressures on mass consumption. The approach used involved an initial planning stage, during which the research question was outlined; a design phase, where the authors delegated areas of research based on expertise; a preparation phase, beginning with wide-scope literature (which was narrowed as the process continued); a data collection phase, where the relevant information was collated from the literature search; an analysis phase, in which conclusions were drawn based on critical analysis of the information; and, finally, a reporting phase, during which the authors wrote their findings and opinions into the finalised review.

A range of both historical and contemporary literary sources was reflected upon to draw comparisons between economic and government solutions surrounding the consumption of resources in times of need. An exhaustive review of the relevant patents was conducted to ensure that an accurate picture of the history of RPF production was obtained. In the context of taking an interdisciplinary approach, using a wide range of resources was necessary to the critical analysis of various methods of complex problem solving from design, scientific, political, sociological, economic and consumer perspectives.

The research involved the analysis of both quantitative and qualitative data to gain a deeper understanding of the complexities behind the research question. Quantitative data was taken from reputable sources such as reports issued by the United Nations (UN) and the Waste and Resource Action Programme (WRAP). Qualitative data were obtained through a systematic review of the relevant literature, including from scientific journals as well as reputable, high-quality grey literature, including industrial and parliamentary reports by companies such as the Ellen MacArthur Foundation. Recent consumer surveys were also analysed to underpin the motivations of switching behaviours towards sustainable fashion and shopping habits. Where data were obtained from grey literature, efforts were made to corroborate the information from two different sources to increase its validity. Keywords such as 'regenerated protein fibres', 'fashion speedcycles', and 'circular economy' were used as a starting point for finding relevant literature. Once a literature resource was found, the abstract or executive summary was examined, and if found to be of interest, the remainder of the relevant information was read and obtained.

This wide combination of sources provides a more holistic account of both the economic and societal pressures that must be considered when transitioning to a circular economy and a more sustainable future. The authors of this paper have each used their disciplinary backgrounds to explore the context of the research from different perspectives, which were then brought together to create a unique and collaborative viewpoint. The interdisciplinary approach taken combines that of an experienced fashion and textiles practitioner and researcher with that of a chartered environmentalist in the field of green chemistry. Alongside these fields, socio-economic and historical influences upon the subject matter have also been explored to offer a much needed, human-centred perspective on the topic of creating systematic change.

3. Results

3.1. Fibres from Waste Foods

Food waste represents a crisis of epic proportions for humanity on a global scale and is the focus of several of the SDGs, particularly Goal 12: Responsible Production and Consumption [19–21]. It is estimated that one-third of all food produced on the planet goes to waste, amounting to almost 1.3 billion tonnes annually [22]. A large proportion of this waste is due to harvesting and production, but a recent 2021 report by the UN states that 931 million tonnes of food waste was generated by the retail sector to the home consumer [23], with an economic loss of over USD 400 billion a year [24]. In the UK alone, 9.5 million tonnes of food waste was generated in 2018, a 2021 report by WRAP [25] has estimated, representing a revenue loss of GBP 19 billion and theoretically producing 25 million tonnes of greenhouse gas (GHG) emissions. While there is no direct data for comparing the food waste post-farm gate to pre-farm gate in the UK, WRAP attempted to estimate it through an exhaustive literature review of similar data from other countries and predicted that food loss (both through waste and surplus) pre-farm gate could be as much as 3.6 million tonnes, meaning that this sector could account for more than retail and hospitality combined [25,26].

Hence, there is the potential to address two of the largest issues in the modern world; the excess waste generated through the food processing industry and the environmentally detrimental demand for fibres and materials of the textile industry. The utilisation of food waste as a feedstock for extraction or conversion into fibres would theoretically reduce the amount of waste generated by the food sector while reducing our reliance on petrochemical-derived fibres and the pressure on the overproduction of natural fibres such as wool and cotton.

Although RPFs are the main subject of this paper, textile materials that have been developed from food waste can take many forms. Over the past decade, a resurge of interest in the development of novel and sustainable fibres has led to an extensive expansion of the traditional categories of natural or synthetic fibres, which now include subcategories such as 'bio-based', 'biofabricated', and 'biosynthetic' [27]. Bio-based materials are derived from biomass (organic waste) "that can have undergone physical, chemical or biological treatment and include materials derived from plants, trees, or animals" [28]. Alongside RPFs, bio-based materials such as orange fibre [29] and Piñatex [30] (see Table 1 for more examples) are defining new circular manufacturing systems through the utilisation of food industry waste. Figure 1 demonstrates the different types of fibres that can be created from various sources of food waste.

Table 1. Materials from food waste used in textile applications.

Brand/Trade Name	Raw Material	Country of Origin	Material Type	Textile Material	Applicable Industries
QMILK	Milk	Germany	RPF for woven, knitted and non-wovens	Lightweight fibre	Fashion, textiles, automotive, medical and cosmetics
Orange Fibre	Orange peel	Italy	Regenerated cellulose fibre for knitted and wovens	Lightweight fibre	Fashion, textiles

Table 1. *Cont.*

Brand/Trade Name	Raw Material	Country of Origin	Material Type	Textile Material	Applicable Industries
Argaloop BioFibre	Oil-seed hemp, oil-seed flax, pineapple leaves, banana tree, cane bagasse, rice straws	Several countries	Regenerated cellulose fibre for knitted and wovens	Lightweight fibre	Fashion, textiles
Piñatex	Pineapple leaves	Philippines	Plant fibre composite with polylactide (PLA)	Leather alternative	Fashion, accessories, soft interiors, automotive
AppleSkin	Apple pulp	Italy	Plant cellulose composite with polyurethane (PU) for nonwovens	Leather alternative	Fashion, accessories, soft interiors, automotive
Vegea Grape Leather	Grape skins and stalks	Italy	Plant cellulose composite with PU for non-wovens	Leather alternative	Fashion, accessories, soft interiors, automotive
Bananatex	Banana leaves	Philippines	Plant fibre for wovens	Hardwearing, durable fibre	Outerwear, travel accessories, soft furnishings
SweetFoam	Sugarcane waste	Brazil	Poly(ethylene vinyl acetate) (PEVA) bioderived copolymer for foams	Flexible, impact-absorbing foam	Footwear
Chip[s] Board	Potatoes	UK	Bioplastic for components	Bioplastic, strong, rigid	Glasses frames, buttons, components

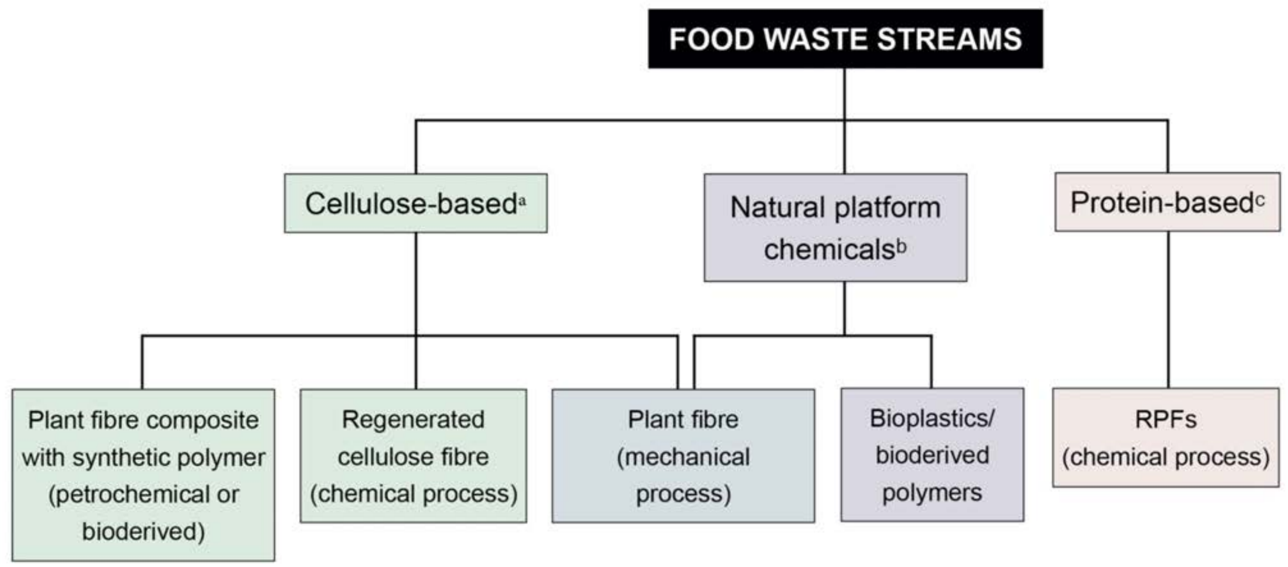

Figure 1. Types of textiles materials from food waste. [a] Cellulose extracted from plants and used directly (seed or stem fibre) or in regeneration process; [b] naturally occurring chemicals (e.g., sugar) extracted from a plant source and used in a polymer synthesis process; [c] protein extracted from a plant or animal source and used in a regeneration process.

3.1.1. Contemporary Food Waste Fibres

Over the decades, industrialisation has caused the exhaustion of our planet's natural reserves [31]. Humans are now overusing the Earth's biocapacity by at least 56% [32]. Roughly 33% of land and 75% of freshwater resources are allocated to agriculture [33], leading to increased environmental pollution; 300–400 million tonnes of waste (annually) are disposed of in the oceans, creating 70,000 km^2 of dead marine areas [34,35]. Loss of land and natural habitats will also create extreme global living conditions, increasing the risk of further pandemics caused by the rapid spread of disease between humans and animals [36]. If our current path continues, it is predicted that we will enter a sixth mass extinction (which some argue has already arrived) [37], where millions of species will be lost [34].

In an effort to solve such largescale issues, a circular economy is often employed [38]. A circular economy is a framework for eliminating waste through the continuous use of products and materials [39]. The three common principles of a circular economy are reduce, reuse and recycle [40] and can take many forms within the textile sector, such as clothing swaps, textile recycling or upcycling, all of which keep textile materials in circulation for a longer period of time. In reality, however, we still have a limited understanding of the lifecycle impacts of a circular economy [41] and, as McQuillan [38] points out, "our human-made cycles always leak—either energy or materials or both". Banwell et al. [42] challenge the concept of an infinite recycling loop, stating that non-compostable materials like polyester should be phased out and new fibres, however 'recyclable,' should not be developed if they cannot re-enter the biosphere through composting or degradation. In this context, a new range of bio-based synthetic textiles created from agricultural and/or food industry waste is also beginning to emerge. Table 1 shows a variety of circular, contemporary textiles developed from such waste and highlights the applications of each material. It should be noted that some of these materials are composites with synthetic polymers that are often marketed as being derived from food waste but incorporate polymers that are not food waste derived (e.g., PU, PLA) and that may limit or negate the circularity of such materials.

As the fashion industry races to develop novel solutions to rid itself of its reputation as a polluting force, to be replaced with one that is regenerative, such bio-based fibres are becoming increasingly in demand [43]. Independent designers, luxury fashion, and high street brands alike are investing time and money into tech start-ups or are setting up their own in-house research and development labs to create niche materials. Fast fashion giant H&M, who has been regularly scrutinised for its wasteful practices and has admitted to burning excess clothing in the past [44], has collaborated with several textile developers to create its Conscious Exclusive Collection. After winning the Global Change Award (GCA) in 2016 (initiated by H&M), orange fibre is currently in commercial use in H&M's Conscious Exclusive collection [45] alongside Piñatex, Vegea (winner of the GCA in 2017 [46]) and Argaloop BioFibre (winner of the GCA in 2018 [47]). Other brands within the H&M Group, including & Other Stories, COS and Arket, are also using such bio-based fibres to improve the sustainability of their own collections.

3.1.2. Regenerated Protein Fibres

The first recorded development of man-made RPFs was in 1894, with Miller producing a fibre called Vanduara silk, made by forcing a concentrated, heated gelatine solution through narrow capillaries to form fine threads [48–50]. The process of wet-spinning RPFs was later pioneered by Todtenhaupt when he developed a method for wet-spinning casein fibres in 1906 [51,52]; this method involved denaturing protein using sodium hydroxide and solubilising it into a viscous spinning 'dope', which was then extruded into an acidified salt coagulation bath to form fibres; this process was refined further by Ferretti in 1937 [53,54]. RPFs found limited use until the advent of WW2 put huge pressure on natural fibre production due to the heavy reliance on wool and silk by the armed forces. The rapid development of spinning methodology is reflected in the majority of some 146 patents

pertaining to RPFs dated between 1930 and 1950 [55]. Most of the process developments were aimed at improving the functional properties of the resulting fibres. Due to the fact that the concept of 'green chemistry' would not be pioneered by Anastas and Warner until 1998 [56], many of the chemicals and processes used prioritised functionality over waste generation, worker safety and environmental impact. A comprehensive review of the RPF manufacturing practices during the 1940s shows that not only were large quantities of sulphuric acid used in the coagulation baths, but formaldehyde was very commonly used as a hardening agent for the resulting fibres to improve their tensile strength, especially their wet tensile strength; this caused myriad issues revolving around waste treatment and worker safety [10].

There have been several attempts to commercialise RPFs since the wars, with the most recent being German company QMILK having produced a quality, organic RPF from milk waste (casein). This fibre is manufactured through a low input process, which the company claims to be zero-waste and free of hazardous chemicals [57]. Anke Damask, the creator of QMILK, started her own label under the name Mademoiselle Chi Chi in 2011, using her uniquely developed milk fibre in 50% of her collections [58].

3.1.3. Textile Supply Chain and Use of Resources

Due to the urgent need to reduce the environmental burden of the FTI, the increased implementation of a circular economy in manufacturing and business development appears to be a positive move forward. At the same time, there is a significant risk that intensifying the circulation of materials and products in certain parts of the value chain could lead to unexpected outcomes at the system level [41], which could be harmful to the environment and business practices alike.

Alongside the potential environmental benefits associated with materials created from agricultural waste, there are several opposing factors to be considered. These bio-based materials are all derived from biomass (or waste) feedstocks; however, there is a concern that as demand for such materials increases, there will be an incentive to harvest first-generation crops for new textiles [43]. The HM Group's involvement with bio-based materials is a prime example of this; although such textiles are currently being used in small collections, H&M currently offers 12 to 16 collections per year (refreshing them weekly) [59] and, in 2018, had USD 4.3 billion worth of unsold apparel [60]. As the bioeconomy increases and companies such as H&M expand their sustainable collections, they run the risk of working with less transparent suppliers as well as creating more wastage from unsold clothing. Depending on the initial source of agricultural or industry waste, there is also the risk of the raw material one day running out. This, again, could switch the company's interest towards first-generation bio-based fibres, creating further issues around deforestation and loss of biodiversity.

The biodegradability of materials is another area for consideration. There is a misconception that all biopolymers are biodegradable [43]; however, they often require the correct method of processing at end of life to avoid off-gassing (the release of chemicals into the environment). Additionally, the blending of compostable, bio-based materials with traditional synthetics such as polyester or even natural materials that have been processed using chemicals such as bleach could pose further issues for disposal. Such textile materials would initially have to be separated, requiring further energy and resources [61].

End-of-life aspects such as biodegradability and compostability have been flagged as an area that often lacks transparency within the context of bio-based solutions [27]. The term 'end of life' is often used in the context of a product that is no longer in use by its owner, suggesting that it serves no further purpose [62]. As many of these new materials are still in their infancy, there is little information of their impact upon disposal as well as their potential environmental impact if production is to be scaled up to meet demand. A full lifecycle assessment (LCA) would be required for each new material to determine areas of concern, not just for current production levels but for the future.

In terms of early RPFs, there is also a gap in information surrounding the full environmental impact throughout the supply chain, from raw material to disposal. As sustainability was not a serious topic of discussion until the launch of the Brundtland report in 1987 [63,64], information such as energy usage, water wastage and impact upon disposal does not exist in the same way. Adding to this, due to the lack of success of RPFs, much of the documentation of their manufacture was destroyed after WW2 due to the embarrassment of a 'failed experiment' [65]. While this lack of information poses a challenge, it also represents an opportunity for research to be performed using the historical precedent set out during the 1940s and 1950s but with a modern, sustainable approach, considering the whole supply chain from waste generation all the way through to end of life.

3.2. Economic Influences

During wartime, large amounts of government funding were put into the development of novel RPFs to alleviate pressures on materials such as wool and cotton. Civilian textiles were mostly being used for military uniforms, although the lack of international trade also contributed to shortages around the globe; during WW2, roughly 65% of the production capacity of the textile industry was devoted to the war effort [66]. Alongside government funding, numerous other tactics were used to control the flow of textiles and limit the public consumption of fashion items. The UK imposed textile rationing in 1941, forcing consumers to become more creative with their limited purchasing power and to adopt a 'make do and mend' attitude in support of the war effort. The experiences and methods of this era can be reflected upon in conjunction with our own current (environmental) crisis and used to address the economic challenges we face today.

In comparison to the WW2 era, today, the fashion market includes many segments and business models, reflecting both the diverse needs of consumers and the growing economies of scale within the industry. By the mid-1970s, fashion brands had begun to copy catwalk styles at much lower cost, supplying cheap fashion products to retail markets within months [67]. This business model expanded rapidly throughout the 1980s and was described by some as the 'democratisation of fashion' [67]. Once exclusive luxuries were now accessible to everyone [68], and whilst clothing had historically represented social class, the wardrobe could now signal other aspects of social identity such as age and gender [69].

In comparison to household incomes, fashion and textile items are much cheaper today compared to just a few decades ago. As the price of clothing has fallen, cheaply made and low-quality fashion dominates the market, allowing consumers to purchase more than is arguably necessary [64]. In the 1950s, 30% of the household income (UK) went to clothing purchases, and, in 2009, that figure dropped to 12%, but with a larger amount of items being purchased [70]. Today, the average household in the UK spends 3.7% of its annual income on clothing [12,71,72], yet the number of purchases has still increased due to the decrease in prices.

3.2.1. Government Incentives for Regenerated Protein Fibres

During the 1930s and 1940s, RPFs were heavily invested in by several governments as not only a solution to material shortages but also as a way of representing national pride. Italy, before the advent of WW2, was already a powerhouse in the textile world, and the rise of the futurism movement made new and novel materials for fashion very attractive. Ferretti's improvement to the casein spinning process pioneered by Todtenhaupt coincided with the rise of Mussolini in the political leadership in Italy. Mussolini was very keen on Italy achieving economic and commercial self-sufficiency, so he whole-heartedly endorsed Ferretti's process, even to the point that during the war, it was law that all Italian fascist flags had to be made out of Italian made casein fibres (named *Lanital*, later *Merinova*) [73]. The Italian military also used casein-based fibres in military uniforms, blankets and boots, believing that it would be resistant to poison gas [74].

At the time, Italy was wasting billions of pounds of excess skimmed milk a year so the invention of *Lanital* was heralded by Mussolini as a key breakthrough, allowing 3.7 kg of fibre to be produced per 100 kg of waste milk. Mussolini was so invested in the artificial textiles coming out of SNIA Viscose that the government granted large amounts of money for the continued development and production of *Lanital* and rayon [75]. The government even issued regulations on the blending of imported fibres with autarchic Italian-made fibres [76]. Many forms of promotional advertising can be seen from around this time, including video documentaries on the production of *Lanital* and even a poem written by the founder of the Futurist movement, Filippo Tommaso Marinetti, published in pamphlet form and illustrated by Munari, which served to propel *Lanital* production and popularity [77,78]. The popularity of *Lanital* took a severe hit after the Italian 1940 campaign in France, where it is thought that rubber-soled *Lanital*-infused boots caused 2000 cases of frostbite [74].

Italy was not the only country to push for the development and commercialisation of RPFs utilising locally produced waste. A 1940 British patent by Imperial Chemical Industries (ICI) [79] details the production of synthetic fibres from peanuts, which led to the commercialisation of the peanut protein fibre *Ardil*, so named after the location of the pilot plant (Ardeer in Scotland), between the years of 1951 and 1957 [80]. In the first half of the twentieth century, the UK was still importing 8 million tonnes per annum of peanuts from its colonial territories. The main use for peanuts was the extraction of peanut oil, which left roughly 50% of the peanut as waste; this was originally used as an animal feed but, through an extraction process, the protein (which represents ~50% of the residue) [81] could be isolated and used to make fibres for textile usage. ICI developed a method involving the dissolution of the protein in solutions of urea and sodium hydroxide to denature and unfold the globular protein arachin, which could then be wet-spun to form fibres that supposedly had characteristics similar to wool [82]. Similar to other RPFs, the advent of WW2 and the corresponding shortage of wool encouraged investment in the fibre, as well as advert campaigns to try and persuade the British public of the advantages of *Ardil*; the phrase "Happy families with Ardil" [83] was used during the marketing campaign. Even after the end of hostilities in 1945, ICI was still devoted to *Ardil*, as seen by the investment of GBP 2.1 million to produce a new manufacturing site in Dumfries [84]. However, the falling price of wool post-war, along with the rise of other artificial fibres and the increasing price of peanuts, put pressure on *Ardil* as a commodity. The final nail in the coffin was the shortage of peanuts as a result of the failure of the East African peanut scheme [85], which caused the production of *Ardil* to cease in 1957 [84].

3.2.2. The Case for a Mixed Economy

The prevalent fast-fashion paradigm results in an abundance of cheap products in the market [86], placing individual customers in a paradoxical situation. For many reasons, buying long-lasting products can be much more difficult than buying low-quality products [87]. Although there is a growing demand for sustainability in the fashion industry, demand for fast fashion products at fast fashion prices still exists [88].

At present, fast fashion is still a dominant force. Its complete eradication would have huge implications in terms of inclusivity and affordability across different consumer demographics. A study on the sustainable consumption habits of consumers in Spain [89] found that expensive pricing was the second-highest deterrent of purchasing sustainable fashion, with uncertainty of greenwashing being the most common reason. Due to this, it is important to develop sustainable and transparent models for both fast and slow fashion economies, capable of meeting the real needs of consumers.

According to WRAP [90], on average, clothing is used for 3.3 years before it is discarded or passed on, with items such as coats and dresses being kept for the longest. Reports and government action plans appear to favour longevity as the route to sustainability. WRAP's Clothing Longevity Protocol [14] suggests that businesses should employ a "minimum standard of good practice", which should be "embedded across the product range, complementing specific design innovations such as anti-fading and anti-pilling technologies and reinforcing brand value by providing a means of quality assurance”. There could, however, be various hidden environmental costs to using such additional finishes, including the use of additional chemicals, water, and energy in the manufacturing process. Indeed, if the item is worn on a regular basis and succeeds to reduce the environmental impacts per wear, additional impacts may occur through care and laundering, especially if physical durability has been achieved through coatings or features which require dry cleaning [16].

It could be argued that a shift in cultural mindset must take place before switching to a slow fashion system built for longevity. A McKinsey Company report [91] found that one in three young women in the UK consider garments to be old after just one or two wears. Until consumers adopt ‘socially responsible consumption’ [92] habits and begin to favour ‘better’ (for both person and planet) over ‘new’, a system created for slow fashion alone will surely fail. The question of textile quality also comes into play here. Quality as a term can be interpreted differently across various situations and differ amongst products, people, and places. A product of ‘high quality’ is often associated with a higher retail value or a ‘luxury’ market. For a genuinely sustainable slow system to be effective, it must also reflect a variety of price points and be inclusive for all consumer demographics.

3.3. Cultural Attitudes

According to Manzini [93], simply redesigning existing products and making eco-efficient improvements to manufacturing processes is not enough to create a more sustainable future. Instead, changes in consumer behaviour and attitudes are needed to stimulate a drastic change in consumption patterns by establishing a connection between individual consumption and the environmental impact of industrial production [64]. Vezzoli [94] argues that radical innovations, beyond technological development, that also stimulate new partnerships between stakeholders as well as new sustainable relationships between consumers and products are needed.

3.3.1. From Quality to Quantity

Over the past 50 years, the way in which we produce and consume fashion has changed drastically [10]. Alongside a growing population, excessive seasonal collections [95], low prices [96], discounts and promotional campaigns, the ease of online shopping, and the influence of social media [97] have pushed individual consumption to the limit [31].

As discussed in Section 3.2.2, although consumption has increased, the number of usages has decreased by 36% compared to just 15 years ago [39]. It is suggested that this reduction in use is not only a result of our temptation to buy new garments but is also a consequence of cheaply made, low-quality garments [64,98–100], which can result in a lack of attachment between product and consumer [31,100].

Quality is a broad term within the FTI and may reflect a range of different attributes, such as how well a product is made, what it is made from, how long it lasts or the way in which it is used or cared for. The Textiles Institute [101] defines quality as “the totality of features and characteristics of a product or service that bears on its ability to satisfy stated or implied needs” or as “a relative term used to indicate the perceived merits of similar products for the same end use.” As discovered throughout the literature, the perceived quality of RPFs had a huge impact on their commercial success throughout the early to mid-1900s. For example, garments made from casein were said to be of low strength [84] and difficult to care for due to high moisture absorbency, and the garments would often end up being cut up for rags after just a few wears or washes. Moving into a new era of sustainability, we should question how quality and sustainability might align to meet real consumer needs, whether for a fast or slow circular economy.

Current literature in this area generally tends to associate terms such as ‘slow’ and ‘quality’ with sustainability, insinuating that slow equals better when better actually de-

pends on circumstance and fitness for purpose. This can be defined by a range of performance characteristics, including durability, appearance retention, and ease of cleaning, and some features that are specific to a certain type of product, such as water repellency or flame retardancy [102]. A recent study of sustainability within the fast fashion industry [103] frames product quality as a “vertical attribute that contributes to the lifespan of the product (e.g., quality of stitching, dyeing process, fabric sturdiness)”; the study shows that fast fashion has an incentive to produce multiple styles and ‘micro’ seasonal collections in response to uncertain and quickly changing trends, and that this is a key driver of low product quality within the industry.

As the availability of trends increases, quality is likely to decrease further as consumers become more responsive to fashion and prioritise style and low prices over durability [103]. Another study into the shopping intentions of young people in Hong Kong and Canada [104] found that the consumers desire for immediate gratification through the purchasing of fashion was one of the main barriers to adopting more sustainable shopping habits. Through its quick turnover of affordable, low-quality styles, the fast fashion model can exploit this segment, offering up-to-date designs and the satisfaction of continually evolving temporary identities [105].

3.3.2. Challenging Mindsets

Rissanen [106] believes that the FTI is “still in a mindset of limitless production, mainly made ‘possible’ by synthetics derived from fossil fuels that are not bound by limits of land use.” Although RPFs might offer a technical solution to some of these problems, as discussed, the issue of consumption is not to be forgotten. As we begin to design new systems for the FTI, current behaviours surrounding our relationships with garments must be challenged and redefined within these systems. McQuillan [38] believes that this would require a significant reduction in production and a redistribution of manufacturing locations, creating a connection between product, environment and society.

Although a pertinent issue, cost is only one of the barriers to sustainable consumption. Style, quality, colour, and a continuous desire for the latest trend can all affect consumer purchasing habits [107]. As a result, a growing number of studies are beginning to outline such consumer intentions towards adopting a more sustainable mindset and lifestyle [108]. Bonini and Oppenheim [109] argue that although there is a large amount of awareness surrounding environmental issues, this does not tend to discourage most individuals from overconsuming or purchasing unsustainable products. Joy et al. [104] agree with this claim and, through their own study, show that “fast fashion consumers, often share a concern for environmental issues even as they indulge in consumer patterns antithetical to ecological best practices”.

On the other hand, a Unilever study [110] showed that 33% of adults surveyed (in five EU countries, including the UK) chose to buy from brands they believe are social or environmental responsible; 53% of shoppers said they feel better when they buy products that are sustainably produced, and 21% would actively choose brands if they made their sustainability credentials clearer through labelling. Alongside brands and individual consumers, transitioning to a sustainable or circular economy requires genuine collaboration across multiple stakeholders [111]. Niinimäki [64] argues that the most influential way to change such industrial systems towards sustainability is through government, legislation and regulations that directly impact manufacturing requirements.

One of the reasons for the RPFs failing was that they were associated with hardship and substitutions and were largely overshadowed by new and exciting petrochemical-derived fibres such as nylon and polyester, which offered never-before-seen fabric properties of strength, durability and ease-of-care. There was heavy investment from several governments into promoting RPFs to the public, but the negative connotations associated with them was too great. In contrast, the modern consumer’s opinion of petrochemical-derived fibres is shifting from the excitement of the 1950s to the 1990s to concern over these fibres and the effect they are having on the environment. This growing dissatisfaction with the current state of the fashion and textile industry represents an opportunity for RPFs to return without the negative connotations of the past.

3.3.3. Matching Textile and Garment Speedcycles

It is evident that most current circular design approaches favour a 'slow' fashion lifecycle, of which 'quality' garments are built to last using methods such as design for recyclability or design for extended use. The research undertaken by Goldsworthy et al. [16,18] for the Mistra Future Fashion Programme, however, suggests that there is an urgency to also design better 'fast' circular models. As reported by WRAP [112], "extending the life of clothing by an extra nine months of active use would reduce carbon, waste and water footprints by around 20–30% each." One issue with only focusing on product longevity is that durable (or slow) materials—such as virgin or recycled polyester—often end up being used in fast fashion products with a short life span. As pointed out by McQuillan [38] and Banwell et al. [42], such durable materials are often non-biodegradable and, in the context of polyester, can take at least 200 years to degrade and will leak contaminants back into the ground as they do so. As discussed by Goldsworthy [16], "by reducing our focus to only a 'part' of the system (the use phase), we are playing into the hands of 'unintended consequence' and often simply shifting impacts further along the product lifecycle, albeit out of view."

Perhaps it is the association between fast fashion and poor quality that leads designers and researchers alike to favour a slow fashion lifecycle. On the other hand, fast fashion is popular for a reason, and not everyone can afford to buy into a 100% slow fashion lifecycle, where products are often more expensive to reflect longevity and durability. In her research of speedcycles, Goldsworthy [16] notes the time taken to produce a raw material in comparison to the length of the use phase. A grown material such as cotton takes a relatively short time to produce (fast) in comparison to a non-renewable material made from oil, which takes thousands of years to form (slow). This provides a contrasting view in comparison to the assumption that natural equals slow (and often better) fashion and that synthetics are for fast fashion. These pre-assumptions of fast or slow are often misleading; if production methods are inconsistent with the expected lifetime of a product, then we are left with an unbalanced lifecycle [16].

In the context of circular textiles and garment speedcycles, appropriate materials need to be developed and selected by designers to be used in fashion products where the duration of use by the owner has been noted and understood [16]. As discussed by Remy et al. [59], "innovation in the way clothes are made has not kept pace with the acceleration of how they are designed and marketed." Fletcher [113] prefers to use the term 'slow fashion' in the context of a 'philosophy of attentiveness' as opposed to time and speed. This philosophy is mindful of the needs of its various stakeholders across the supply chain and of the impact producing fashion has on workers, consumers and ecosystems [104].

4. Discussion

There is an argument that designing fibres that are intentionally short-lived could provide an alternative to the prescribed slow-fashion solution to the sustainability crisis in fashion. Historical RPFs were designed to provide a 'stop-gap' solution in a time of intense material shortages. During wartime, the aim was not to produce materials that would last a lifetime, as it was hoped that the war effort would be short-lived. This led RPFs to an association with being inferior to the materials they looked to replace. However, within the modern fast fashion movement, clothing is not designed to last a lifetime and is, in fact, designed to last a single season. This might open possibilities to match the fabrics' useful lifespan with the speed at which fashion trends occur; if the fabric only needs to last a few months or even just a few wears, why design it to have the durability and longevity offered by polyester, acrylic, and nylon? Even better, if the material could be designed to degrade without leaching any unwanted chemicals into the soil, there is potential for the circular life cycle of the fabric to be relatively short. Using casein as an example, the

nitrogen and nutrients from waste milk could be re-introduced into the biosphere through the composting of casein-based textiles. These nutrients could be used in the feed for cows, which would then produce more milk, of which the waste could be converted back into RPFs. A full LCA of the entire process, from conversion into milk via the cows all the way through to the input of the fabric back into the biosphere, would need to be conducted and compared to the current state of the art to ensure that the process is an improvement in relation to sustainability.

Alongside a switch in business attitudes towards fast and slow fashion systems, analysis shows that consumers drive demand for products. Therefore, focusing purely on eco-materials or ethical manufacturing principles misses the opportunity to take a more holistic approach. It could be argued that the sustainable revolution of the fashion and textile industry will begin with consumers changing their purchasing habits, so engaging and educating the public will be crucial in the development of new and novel sustainable solutions.

In the context of disposability, the issues leading to the demise of the RPFs of the 1900s could be seen as advantageous within the modern fashion world. Contrary to the post-war world, public opinion of petrochemically-derived fibres is at an all-time low, with the average consumer now being far more educated on their environmental impact and persistence in the environment at end of life. Along with this, the average time that items of clothing are in use has decreased massively since the 1940s; this means that the issues with the longevity and quality of the RPF fibres are far less of an issue. In fact, designing fabrics that are regenerative via composting and can be re-introduced into the food supply chain within a reasonable timeframe could potentially and synergistically match the current fast fashion trend with the vast amounts of food waste that is generated within the developed world.

Another comparison that can be drawn from the historical investigation of this research is that of a localised economy. During the world wars, the localisation of industry was essential due to the limitations of trade. RPFs were a prime example of this, with different counties adopting different feedstocks depending on their availability within the countries' borders. Post-war, the globalisation of industry gave rise to offshore manufacturing, with the production of feedstocks, processing, and product commercialisation very rarely happening within the same country (or continent), giving rise to vast environmental issues involving the emissions created by shipping and freight. Currently, there is a growing trend away from globalisation, back towards the localisation of industry. The need for this has been further emphasised by the COVID-19 pandemic, with the need for production to be self-sufficient and robust to external factors. Once again, the synergy between the approach taken during the wars to allow for more robust manufacturing and those beginning to be recognised as essential in the modern world to reduce the environmental impact of industry opens an exciting opportunity to learn from the lessons of the past to strive towards a low carbon economy.

While the slowing of the fashion sector is commonly viewed as the necessary breakthrough to creating a sustainable future, this will require a vast change in the cultural mindset of the consumer. As discussed, the solution to the environmental impact of the fashion and textile sector cannot be solved by a single concept but a holistic approach considering the entire sector, from feedstocks and production through to end of life. This will require a collaborative effort from a myriad of sectors, from stakeholder, manufacturing and legislative bodies through to commercial, advertising and government bodies. Most importantly, the consumer must be educated and given the knowledge required to recognise what is truly sustainable.

5. Conclusions

The aim of this research was to analyse how RPFs from food industry waste could offer a new perspective on our interpretation of fast and slow speedcycles whilst alleviating pressures on mass consumption. The research also aimed to identify gaps in both the historical and contemporary data surrounding the production of RPFs from a sustainability viewpoint, allowing opportunities for further investigation. The major contribution of this study is to critically analyse the academic literature surrounding the implementation of a circular economy within the FTI and a revaluation of 'fast' and 'slow' within the fashion life cycle. In taking a critical and holistic approach to evaluating the principles of a circular economy in the area of bio-based materials and RPFs, it has become clear that the fashion industry is far from creating sustainable change and, in some cases, may do more damage than good. Until we find a successful way to implement holistic system changes and reduce consumption (in a way that is inclusive and attainable for everyone), our efforts in producing novel, eco-friendly materials alone are redundant.

This paper has revealed a gap in academic literature surrounding the end of life of new, bio-based materials and RPFs. Based on this outcome, a full LCA of new generation bio-based materials and RPFs is suggested as the next stage of research. Any future research in this area should also take into consideration the potential of increased consumer demand over time. The concept of a circular economy must also continue to be reviewed with a critical eye, with higher emphasis placed on aspects such as chemical and energy usage, off-gassing, biodegradability and compostability. Consumer-based studies into the appeal of purposely made, disposable fast fashion in comparison to a slow approach is another area of interest for future research. This study has outlined the importance of consumer engagement at all stages of the lifecycle, from design decisions to how garments will be disposed of. Making consumers a part of the decision-making process and adapting marketing content to be informative and educational in terms of sustainability can help to build stronger relationships between stakeholders and begin to drive responsible consumption habits. This research took an interdisciplinary approach to the subject matter and explored the context of materials created from food waste from a range of design, green chemistry, historical and sociological perspectives. However, to continue with this research and create real solutions to such complex problems, further disciplinary boundaries must be crossed. Expertise from areas such as biology, biochemistry, ecology, geography, marketing, and politics should be combined and embedded to create new knowledge in the area of sustainable development across all industries, not limited to the FTI.

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10.6.3 Paper 3: Referencing Historical Practices And Emergent Technologies In The Future Development Of Sustainable Textiles: A Case Study Exploring "Ardil", A UK-Based Regenerated Protein Fibre

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Review

Referencing Historical Practices and Emergent Technologies in the Future Development of Sustainable Textiles: A Case Study Exploring "Ardil", a UK-Based Regenerated Protein Fibre

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Abstract: We are currently experiencing a global environmental crisis. Our waste culture is leading to huge irreversible damage to our planet and ecosystems. This is particularly evident in both the textile and food sectors, with a system-wide restructuring as to how we consume and source materials becoming ever more urgent. By considering our waste as resource, we can access a vast source of raw materials that is now being recognised as such. Viable materials in the form of waste have the potential for conversion into textiles. However, this proposed solution to our contemporary crisis is not new technology. Throughout the 20th century, science and industry have researched and developed materials from food waste to meet global demand for textiles in times of need, with a major development during the world wars being the invention of regenerated protein fibres (RPFs). For various reasons, this research was abandoned, but much of the development work remains valid. This research critically analyses work that has previously been done in the sector to better our understanding of the historical hindrances to the progression of this technology. By applying modern thinking and scientific advances to historical challenges, there is the potential to overcome previous barriers to utilising food waste as a resource. One of the key influences in the discontinuation of RPFs was the rise of petrochemical textiles. Our current understanding of the detriment caused by petrochemicals warrants a further review of historical emergent technologies. This paper uses Ardil fibre as a case study, and shows that there is a clear disparity between the location of historic research and where the research would now be helpful. Ardil was a British-made product, using peanuts sourced from the British Empire as the source of protein. Techniques used in the processing of Ardil could be better utilised by countries and climates currently producing large amounts of peanut byproducts and waste. Through this research, another historical concern that thwarted Ardil's acceptance as a mainstream fibre was discovered to be its poor tensile strength. However, contemporary garment life cycles are far shorter than historical ones, with built-in obsolescence now being considered as a solution to fast fashion cycles by matching the longevity of the fibre to the expected use phase of the garment, but ensuring suitable disposal methods, such as composting. This research highlights the need for cross-disciplinary collaboration between sectors, with a specific focus on the wealth of valuable information available within historical archives for modern sustainability goals.

Keywords: regenerated fibres; regenerated protein fibres; waste; circular economy; valorisation; garment industry; manmade fibres; textile processing; textile history; Ardil

1. Introduction

We are firmly in a period of environmental crisis, with humanity's impact on the planet becoming ever more evident, and the time before irreversible damage has been caused is rapidly dwindling. Two of the largest sectors contributing to this environmental crisis are the textile and food production industries. The size of the textiles sector has been increasing steadily in recent years, and the garment sector alone is estimated to produce 3.3 billion tonnes of CO_2e annually [1]. Globally, fibre production reached 109 million tonnes (Mt) in 2020, representing a 10-fold increase since 1950, of which synthetic fibres represent roughly 62% of production mass. Global fibre production is expected to increase by another 34% to 146 Mt by 2030. Worldwide fibre production per person increased from 8.4 kg per person in 1975 to 14 kg per person in 2020 [2]. With the global population simultaneously expected to increase by 40% by 2050, the environmental burden of the textile industry will increase rapidly in the coming decades [3]. The increase in clothing purchased can be attributed to several different factors, such as the comparably slow rise in clothing prices when compared to other consumer goods [4], and the advent of the phenomenon known as "fast fashion" [5,6]. With the turnover of fashion being so high, and the cost of clothing being comparably low, the amount of waste generated per annum is vastly increasing with this new model of textile consumerism.

Understanding the environmental impact of different textiles is complex, and the literature often provides conflicting data. For example, Moazzem et al. claim that a key contributing factor to the environmental impact of the textile supply chain is the consumer use phase in garment life cycles [7]. However, a 2017 report from WRAP cites the fibre production stage as the highest contributor to the carbon footprint of clothing, with roughly 11 Mt of CO_2e produced in 2016 (out of a total of 26.2 Mt of CO_2e across the whole supply chain) [8]. These conflicts often arise because the process of measuring and recording the environmental impact of a garment throughout its life cycle is highly complex, making any comparisons across fibre type subject to debate. Recently, a widely used tool for mapping the sustainability of fibre types and materials—the Higg Materials Sustainability Index (MSI)—has come under scrutiny, as it only considers the production phase in its assessment. [9].

The environmental issues and concerns with synthetic fibres are well documented, and have dominated the media headlines in recent years. It is often assumed that natural fibres are more sustainable when compared to synthetics. However, the environmental effect of the production of natural fibres cannot be ignored: the recent increase in the desirability of natural fibres in an attempt to be environmentally conscious has been shown to cause myriad issues. Cotton fibre is a vast industry estimated to employ nearly 7% of labour in developing countries [10]. Operating the cotton industry at this scale comes at a huge detriment to the environment. Cotton is very difficult to grow successfully, requiring huge amounts of water and pesticides to sustain the crop, which occupies only 2.4% of cultivated land but consumes 6% of pesticides and 16% of insecticides globally [11]. Production of cotton uses vast amounts of water; 69% of all water used in fibre production is attributed to cotton, with 1 kg of finished fabric taking about 20,000 litres to produce [12].

Protein fibres also have issues. Farming and harvesting silk also involves intensive and environmentally harmful processes, and is ranked higher than most other fibres on the Higg MSI [13]. Although silk fibre represents a much smaller proportion of the global fibre market than cotton, at just 0.1% of the global market, the value of silk was expected to be USD 16.94 billion in 2021 due to increased desire for this fibre [2]. Wool fibre production has an incredibly high carbon footprint, accounting for 36% of the total carbon footprint in fibre production for clothing in use in the UK in 2009 [14], and the desertification of Mongolia has been attributed to the farming of cashmere goats [15,16]. While, again, these statistics only consider the production phase of these fibres, this must be understood in the context of the renewed interest in natural fibres and the vast increase in demand. One hundred years ago, the quantity of textiles required to meet global demand was far less than today, due to the lower population and the different approach to clothing. A coat lasted a lifetime, as opposed to a fashion season, which meant that the pressure on the production of natural fibres was lower, and the associated environmental impact was limited. The synergistic effects of the increased demand for natural "sustainable" fibres from a more environmentally conscious consumer base, along with the evidenced increase

in environmental impact resulting from overstrained natural fibre production routes, opens up an exciting opportunity for novel research into potential feedstocks for sustainable fibre production. However, there is potential not only in exploring "new" processes, but also in learning from historical precedent to draw inspiration for a more sustainable future.

There is a genuine need for sustainable fibres in contemporary society; however, the problems of overpopulation and lack of raw materials are not new. This was acutely felt during the first half of the 20th century, with the economic pressure created by two world wars and the growing global population. During the interwar period, in response to this hardship and strain on textile resources, government hopes turned to an emerging science—regenerated protein fibres (RPFs). Their revolutionary idea was to use regenerated protein fibres created in a lab to reduce their reliance on natural fibres grown in fields or on animals. In theory, RPFs could be made from an array of protein sources more simply and economically than traditional fibres such as wool, which requires farming livestock [17]. It was hoped that these new regenerated fibres would provide an economical and competitive alternative to natural fibre resources [18], and across Europe many companies began experimenting with RPFs on a commercial scale, in the hope that these fibres would be the future of the textile industry [19]. While there are some examples of contemporary RPFs in today's market, such as QMilch, this paper focuses on historical examples of RPFs.

The process developed during the interwar period to produce RPFs was as follows [20]:

1. Dissolution of the protein in a suitable solvent. This is typically an aqueous solution of a diluted alkali.
2. Denaturing and unfolding the protein molecules into a linear state. In the case of casein this is achieved via the introduction of NaOH which, when given enough time, breaks the proteins' secondary structure. This enables extrusion through small holes within a spinneret.
3. Extrusion of this protein "dope" through a spinneret directly into a coagulation bath in a wet spinning process. This involves controlled precipitation of the protein in the coagulation bath, forming continuous filaments. The coagulation bath usually consists of an anti-solvent—typically an aqueous solution of diluted acid—and other chemical additives. Salt is added to increase the osmotic pressure within the bath, causing fibre shrinkage to aid with protein molecule orientation and to prevent fibres from sticking together. A crosslinking agent (most commonly formaldehyde) is added to improve the tensile properties of the fibre. The filaments can then undergo further mechanical and chemical processes to increase their functional properties, including chemical hardening in a separate bath. The most common chemicals used historically for RPFs are sulphuric acid, sodium sulphate, magnesium sulphate, and formaldehyde.
4. Drawing filaments. A mechanical process of gradually stretching the fibre to aid in protein molecule alignment and increase fibre crystallinity, leading to an increase in tensile strength.

Despite showing early promise, this industry died out after World War II. Some of the key factors in the disappearance of these fibres included problems with tensile strength—particularly wet strength—and the availability of raw materials. RPFs were a revolutionary idea that promised to solve issues of supply and demand, but ultimately failed. However, this method of creating fibres has been shown to have potential in the realm of sustainable textiles, as the protein used can be upcycled from waste. There is renewed interest in this technology, as the need for more sustainable fibres grows ever stronger. It is also possible for regenerated fibres to be broken down post-use, creating a material with a circular economy. At present, further research into environmentally friendly methods of producing RPFs is required, as historically the process of crosslinking proteins uses harmful chemicals (e.g., formaldehyde). In particular, systems supporting the life cycle of these fibres, such as waste collection and composting of the garments, have previously been identified as key areas for further research [21]. This paper explores the reasons for the disappearance of RPFs, and asks what lessons can be applied to sustainable contemporary textile design. By reappraising historical examples of RPFs against contemporary scientific developments, it is hoped that a potential future sustainable method can be demonstrated.

Ardil fibre was chosen as a case study, with the aim of understanding the shift away from these promising early fibre developments and the potential lessons to be gained from past RPF research. Ardil is the brand name of a fibre first developed in the 1930s by the British company Imperial Chemical Industries (ICI). It was made from groundnuts, more commonly known as and hereafter referred to as peanuts (although the literature uses the names interchangeably). Ardil's development coincided with periods of shortage and austerity during the world wars—a time when manufacturers were seeking alternatives to natural fibres. During these wars, textiles were deemed to be of vital importance, with wool for uniforms being considered just as important as bullets [22]. Not only that, but the strain of the war effort on the textile industry was immense, with 65% of the production capacity being diverted to the creation of government fabrics [23]. This vastly reduced the available fibres and fabrics for the general consumer. There was also fear of disruption of the wool trade routes leading to material shortages. All of these factors combined resulted in the heavy investment in and rapid development of fibres that could be produced from alternative feedstocks, such as Ardil. However, Ardil production did not continue beyond the 1950s. By closely scrutinising the development, success, and subsequent downfall of this once highly promising RPF, and by employing modern techniques to critically analyse the sustainability of the process, we can begin a holistic approach to the development of contemporary RPFs.

2. Materials and Methods

This paper combines literature from design, science, and industry to investigate how textile materials can be created from food waste to elevate pressure on finite resources for textiles. The authors used Ardil as a specific example of an RPF as a case study, as it was one of the few examples of a British RPF to be put into commercial production with moderate success, providing useful insights for contemporary textiles. The authors first planned the paper, identifying Ardil as an appropriate case study before outlining the structure of the paper. Next, data were collected using literature searches and by identifying and visiting appropriate collections. This information was then critically analysed by the authors before reporting their findings and opinions on the subject. A detailed review of the RPF patents was used in order to understand the chronological progression of the technology. Using historical sources including newspaper articles, magazines, journals, and archival collections, this paper first outlines the story of Ardil, seeking to understand the nuances behind its development and, for the first time, the reasons for its subsequent failure. Secondly, this is contextualised through a contemporary lens, questioning what knowledge can be applied to the ongoing research and development of contemporary RPFs. A timeline illustrating the rise and fall of Ardil helps explain its place in history and the simultaneous shifts in the global textile market and the wider economy (Figure 1). Three main areas in the story of Ardil are considered:

1. Development of the historical technology;
2. Marketing and public reception of Ardil;
3. Social, political, and economic factors.

This research has been challenging, as there are very few recorded examples of Ardil in contemporary museum collections today. Brooks argues this may be a result of Ardil's poor longevity as a fibre and the difficulty in distinguishing fabrics made from Ardil from other fibres, such as wool [24]. As such, unless there is clear supporting evidence or labelling, many Ardil fabrics may sit in collections unnoticed. The lack of known examples of Ardil and the rarity of academic literature relating to it have previously hindered in-depth research into this fibre, as the material is not easily accessible. Whilst conducting the archival research for this paper, several little-known or previously unrecorded examples of Ardil were discovered. These discoveries have helped to shape further understanding of the prevalence and historical importance of this fibre.

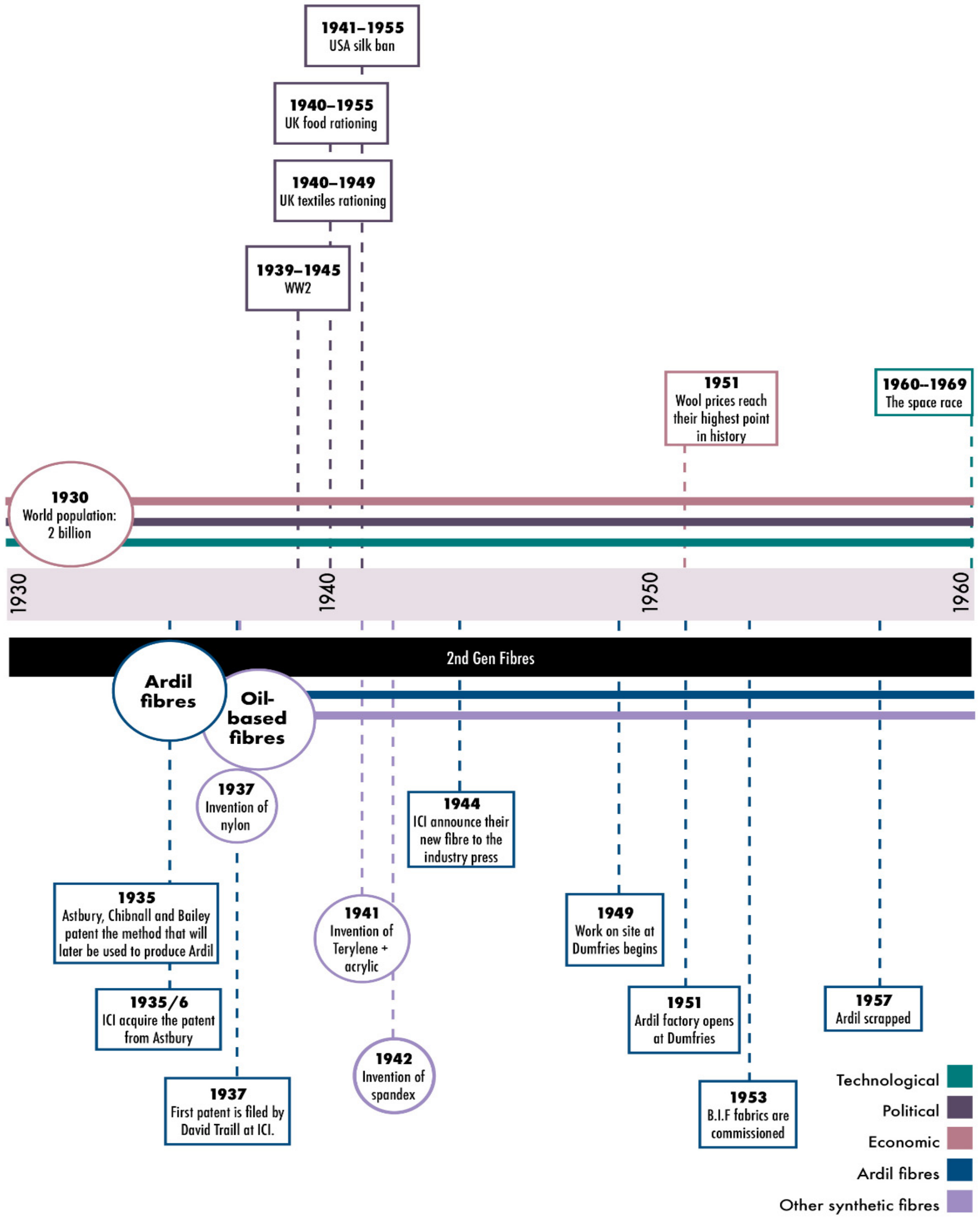

Figure 1. This timeline shows the key events in the development, marketing, and subsequent demise of Ardil fibre, as well as the social and economic events that influenced its trajectory.

3. Results

3.1. Historical Background

3.1.1. RPF Background

The development of RPFs stretches back to the 19th century, with the first known example being a fibre made from gelatine by the scientist Adam Millar in 1894. Following on from Millar's work, other scientists developed RPFs using sources of protein that included maize, soya beans, chicken feathers, albumin, and eggs. It was not until the 1930s that the technology sufficiently advanced to become scalable. In 1935, the Italian scientist Antonio Ferretti created a commercially viable casein fibre, which was marketed as Lanital. The Italians were so proud of their new fibre technology that it was used in the manufacture of Italian army uniforms, under Mussolini's rule. However, the army were not impressed by the poor quality of Lanital as compared to wool [25]. Lanital, like the majority of RPFs developed during the interwar period, proved unsuccessful, as it could not compete with natural fibres such as cotton and wool [26]. Although RPFs successfully mimicked desirable properties of natural fibres such as soft handle, they were easily damaged and became weak when damp [27].

3.1.2. Imperial Chemical Industries Background

ICI was one of the largest science and technology companies of the 20th century. They were responsible for creating well-known products such as Perspex, Polythene, Dulux paints, and hundreds more. Though predominantly a chemical company, ICI were acutely aware of the shifts within textiles, and of the potential role their chemical expertise could play in the sector. In the early 1900s, it was widely believed that the future of the textile industry lay in scientific development and the exciting properties that technology could imbue. Alongside RPFs, this was also the age of development for petrochemical-derived fibres such as nylon and polyester, which would eventually supersede RPFs to become the prevalent materials they are today, but for a time both technologies were equally feted. The work of ICI was a clear example of this, with involvement in developing several manmade fibres, including synthetic fibres from the petrochemical industry as well as RPFs [28].

3.2. Development of the Historical Technology

3.2.1. Invention of the Process

Though ICI were responsible for the development, marketing, and even naming of Ardil, the science behind the fibre originated from the work of William Astbury at The University of Leeds. Astbury worked in textile physics at Leeds from 1928, and held the Chair of Professor of Biomolecular Structure from 1946 until his death in 1961 [29]. He focused much of his work on using X-rays to study biological molecules—particularly wool and hair fibres. His work with Florence Bell on X-ray crystallography of biological molecules revealed the regular, ordered structure of DNA, which laid the foundations for the structural identification of DNA by Crick and Watson in 1953.

In addition to this work, in 1935 Astbury developed a technique for producing fibres from vegetable proteins with his colleagues Chibnall and Bailey at Imperial College London [30]. Their technique involved denaturing globular proteins—a process of chemically unfurling the molecules of protein in order to "refold" it into a fibrous form. These globular proteins are found in different sources of vegetable protein, including hemp seeds and peanuts.

3.2.2. The Role of ICI

To understand why ICI were so interested in Astbury's work, it is important to understand where the technology was at this point in time. Analysis of patents filed relating to RPFs, from their invention in the 1870s onwards, shows that prior to Astbury's work RPFs were more commonly produced from animal proteins. Before Astbury and his colleagues filed their patent in October 1935, only three other researchers had filed patents for RPFs since Adam Millar in 1894. These were Dr Friedrich Todtenhaupt, Herman Timpe, and Antonio Ferretti, whose methods all focused predominantly on milk casein, gelatine, eggs, and albumin. In Astbury's patent, he specifies "Production of silk and wool-like threads from 'vegetable' proteins belonging to globulin group" [31]. This patent would have likely been of great interest to ICI, as it specifically worked with seeds and legumes, as vegetable proteins were in higher abundance throughout the world [26]. Importantly, using vegetable proteins would also cut out the additional and costly step of farming livestock that the previous patents for animal-protein-derived RPFs used.

Quickly realising the potential in Astbury's research, ICI formally purchased the patents the following year [32]. The responsibility of further developing Ardil for commercial use was handed to David Traill in ICI's Nobel Division [33], named after Alfred Nobel, who originally founded the factory at this site [34]. Traill set to work finding the most suitable source of protein to use with Astbury's methods. In patents filed by Traill between 1937 and 1939, he specifies peanuts as well as casein, until the 1940s onwards, where he focuses purely on peanuts [35,36]. Traill's experiments had found peanut protein to be the most suited to his purpose [37]. Peanuts were commonly imported to the UK as a foodstuff, and so could be relied upon as a regular source of protein to work with; the Gambia alone imported 10,275.6 tonnes to the UK in 1935 [38]. The main product produced from peanuts at this time was peanut oil, with the leftover meal used as animal feed or considered waste. As discussed, there were already several examples of casein regenerated protein fibres in commercial production [39], but none using peanut fibre yet (the only other historical example of a peanut fibre being developed commercially was Sarelon in the US, where peanuts can be grown [40,41]). With the parameters set for their new product, Ardil fibre was christened after the location where Traill worked—at an ICI plant in Ardrossan on the Ardeer Peninsula in Ayrshire.

3.2.3. The Chemical Process

The chemical process of creating Ardil was described in 1955 [19]: Peanuts are first crushed to extract the oil used as an ingredient in food manufacture (e.g., margarine) and personal care products (e.g., soap). The residue consists of approximately equal parts of carbohydrate and protein; the protein is extracted, and is washed and dried to obtain a white powder called Ardein, which is primarily composed of a protein called arachin. Ardein is dissolved in caustic soda and extruded through spinnerets into a coagulation bath, followed by hardening, washing, crimping, and cutting into staple fibres ready for spinning (Figure 2a). As discussed in the introduction, the hardening stage often employed the use of formaldehyde as a crosslinking agent; this posed serious environmental concerns with regards to wastewater. This, in combination with the fact that wet spinning as a process is very water-intensive, with large amounts of water being required for every stage of the process, means that even though this protein fibre utilised a "waste" feedstock, the actual environmental impact of the process was likely to be relatively harmful. The undissolved part of the peanut meal is recovered, and is valuable cattle food [42].

As Ardil was not produced as a continuous filament, it was very versatile for spinning into a variety of yarn weights. The fibres could be made into several different deniers to suit garments or interior textiles accordingly. In order to promote and explain their new fibre to potential customers, ICI produced a manual for manufacturers [26]. The manual explains that there were three main types: B, F, and K, each with slightly different properties and subsequent applications. Another important distinction between the types was the shade; Ardil was naturally a fawn colour, with the manual suggesting that to achieve a pure white shade, bleaching was required. This may have been seen as drawback by some manufacturers, as it would affect the shades that could be achieved through dyeing. The reasons for producing these different product specifications for Ardil are not immediately obvious, but the unusual product categories imply that ICI were compensating for shortcomings of Ardil.

(**a**) (**b**)

Figure 2. (**a**) "The moment when 'Ardil' first becomes a fibre": Filaments of Ardil are drawn from fibres in the coagulating bath; Catalyst Science Discovery Centre and Museum. (**b**) "Ardil Protein Fibre Factory, Dumfries" by Henry Rushbury, with the Ardil Tower visible; Catalyst Science Discovery Centre and Museum.

3.2.4. Blends with Ardil

Despite high expectations, during initial testing, it became clear that Ardil was not particularly strong as a fibre; it had poor tensile strength when wet compared to other fibres, such as wool (Table 1) [26].

Table 1. Comparison of the principal physical properties of "Ardil" fibre and wool.

Property	"Ardil" Fibre	Wool
Specific gravity	1.31	1.31
Tensile strength (kg./sq.mm.)	8–10	12–20
Elongation at break (%)	40–60	30

It was therefore decided that Ardil would perform better when blended with wool and other fibres, such as rayon, which would stabilise it. The most notable incentive for using Ardil as a blend was the reduction in material costs when compared to a pure wool fabric [43]. However, there were also benefits to material properties when using Ardil as a blend, which *Silk & Rayon Magazine* reported on in 1945 [37]. Ardil was pitched to customers as a complimentary fibre that enhanced the properties of the other fibres it was blended with; it could be used to make lighter woollen fabrics, it was not subject to moth damage, and it was crease-resistant. Another key consideration in the production process highlighted by the *Silk & Rayon* article is that the variable length of fibres meant Ardil could be spun with existing machinery and, therefore, easily absorbed into company production lines [37]. Ardil was also found to be beneficial in hat making as, although it did not felt itself, it enhanced the felting process when used with wool [44].

In order to achieve the most from their new fibre, ICI encouraged industry partners to experiment with it. As a result, a wide array of Ardil blends were created, tested,

and accessed [18]. It was suggested that blends with a higher percentage of Ardil would be better suited to dress fabrics, where washability was not as intensive or as frequent compared to shirting materials [43]. Ardil was blended in equal parts with wool, and just before the outbreak of war, sufficient fibre was produced on a laboratory scale to enable a number of suits to be made; a number of these suits were still being worn in the early 1950s [42]. Although *ICI Magazine* reported positively about the longevity of these early garments, anecdotal evidence suggests otherwise [45].

3.2.5. Ardil Factory

The ICI board approved Ardil for mass production in 1947. A GBP 2.1million budget for the project was agreed, and work began on the Ardil plant at the Dungan's site in Dumfries in 1949 [30]. The centrepiece of this site design was the Ardil Tower—a monolith to ICI's aspirations for their fibre (Figure 2b). The factory utilised a vertical assembly line, where all parts of the yarn-making process were conducted under one roof. The peanut protein meal was also stored onsite for ease of production. ICI were immensely proud of their new Nobel Division factory buildings, and boasted about the external "buff coloured" bricks and the "special acid-resisting floor" in an issue of *ICI Magazine* from 1950 [46]. Internally, the plant was fully tiled, as cleanliness was essential to the chemical processes of making Ardil. The description of the factory highlights the advancements made in contemporary RPF science, where the involvement of acid in the process would be highly controlled and minimised. When the plant was in full production, the output was around 9000 tonnes per year [42]. The site was ready for commercial production in 1951.

It took over 15 years from the initial idea developed by Astbury in his lab at the University of Leeds to the opening of Ardil's own dedicated plant. Throughout this time, numerous trials and testing of the material were carried out. Recommendations to blend Ardil were introduced to address flaws in its material strength, but despite this ICI still felt confident in the importance of the fibre they had invented.

3.3. Marketing and Public Reception of Ardil

3.3.1. General Public

Though ICI and textile manufacturers had great confidence in their product, they now faced a new challenge—marketing a new and unknown product to the public. After the Second World War, the public were keen to forget the hardship and rationing imposed on them, and to celebrate their post-war wealth. Although rationing of clothes continued until 1949, a desire for newness and convenience underpinned the marketing of many products, and the textile sector was no exception. Advances in science that had resulted from necessity during the war were now being applied to household products post-war. Textile journals from this period are filled with adverts for different coatings and finishes that ease the process of laundering [47]. The public were hungry for new materials and products that science could offer them, and the ease that they brought to their domestic lives. Ardil fit directly into this remit, with one advert declaring "Happy families—with 'Ardil'" (Figure 3a). Directly targeted at the housewife, this advert shows a domestic scene, and asserts that Ardil is a key ingredient to domestic bliss.

Though this was an era of new scientific ideas entering the domestic sphere, a textile made from peanuts was not easily accepted by the public. Many magazines and journals could not resist the humorous connotations of a fibre made from such an unlikely source. A headline from 1944 jubilantly declared that ICI had launched a "Monkey nut" fibre [34]. Another article reports that a wearer of an Ardil frock described it as "just nuts" [41]. Astbury was known to wear an overcoat made from Ardil during his lectures at the University of Leeds [48]; a cartoon published in the *Yorkshire Evening Post* in the same period [49] depicted the coat being pecked at by birds, further evidencing the humorous reception that this novel fibre would have had from the public (Figure 3b). It is notable that Astbury referred to the coat himself as made from "Monkey nuts", as he was not permitted to discuss ICI's new fibre by its brand name [32].

(**a**)

(**b**)

Figure 3. (**a**) Happy families—with "Ardil" advert circa 1955. (**b**) Cartoon of Astbury's "Monkey nut overcoat", *Yorkshire Evening Post*, 1944.

In fact, ICI were so concerned by these sardonic reviews from the press that they sold several garments made from Ardil to the public in secret [48]. Fearing that consumers would be put off by the origins of the yarn, they retailed several Ardil garments labelled as pure wool. This was part of wide-scale marketing test to see if the general public could notice the difference in the Ardil products.

3.3.2. The British Industries Fair

As well as advertising directly to consumers, ICI knew it was important to target the manufacturers who would use Ardil in their products. Established in 1915 by the Board of Trade, the British Industries Fair (BIF) was an esteemed showcase for British products and commerce. In 1953, ICI took a stand at the Earl's Court site of the BIF. ICI regularly showed their products at the BIF, but this was the first time they had shown a textile product, hoping to market it to manufacturers and the public alike. Stand No. R421/518 at the Earl's Court branch of the fair was an extremely large dual-aspect stand at the very centre of the exhibition [50]. ICI occupied more space than any other single exhibitor; the stand was designed by Hulme Chadwick, and was intended to show the fibre's "great versatility and exceptional properties" [51].

An advert for the upcoming show proudly declared Ardil to be "a new fibre of great importance to the textile industry" [52] (Figure 4a). The advert also hinted at several of the factors afflicting Ardil in its development so far. Ardil was referred to as a "new fibre" even though, as previously discussed, the development of Ardil had spanned nearly two decades already. Ardil was also described as "now available in bulk", alluding to the production and scaling problems faced at the plant. The BIF was so prestigious and the

stand so intriguing that it was even visited by the new Queen, who was crowned the following month (Figure 4b) [53]. Tellingly, the Queen is reported to have asked "You tell us of all these remarkable properties. Surely there must be some snags?" [54].

(**a**)

(**b**)

Figure 4. (**a**) "Ardil a new fibre of great importance to the textile industry", 1953; Catalyst Science Discovery Centre and Museum. (**b**) "Her Majesty is seen here examining 'Ardil' protein fibre" at the British Industries Fair, 1953; Catalyst Science Discovery Centre and Museum.

3.3.3. Designers Working with Ardil

In order to showcase Ardil at its best, ICI had commissioned some of the UK's leading textile designers to create fabrics using Ardil blends [51]; the pioneering woven furnishings designer Tibor Reich was one of them. It is perhaps no coincidence that Reich was a graduate of The University of Leeds, where the method for making Ardil was invented. The University's reputation in industry was strong, and Tibor's link to the institution may well have led ICI to commission him for their stand. Tibor Ltd. produced several fabrics using Ardil—most notably a design called History of Shapes (Figure 5), described by one reviewer as a "A tour de force woven on the Jacquard loom in [A]rdil, spun silk, and a metallic thread, which was then screen-printed with a narrative pattern" [55]. Today, one of the same pieces that hung on the BIF stand can be seen in the Tibor Ltd. private archive. The piece is regularly described as being made of Ardil, silk, and Lurex. Upon closer examination of the piece, it appears that Ardil is spun with silk to produce a unique yarn. The Victoria and Albert Museum also holds History of Shapes in their collection, although it is not identified as being made from Ardil. As a result of this research, the catalogue at the V&A has been corrected to record this piece as being made from Ardil.

Figure 5. Furnishing fabric History of Shapes, designed by Tibor Reich, Hungarian, Stratford-upon-Avon, circa 1953. © Victoria and Albert Museum, London.

As a designer, Reich was always interested in working with new materials and concepts. He was already using another novel material called Lurex—a yarn made from thin aluminium foil—in many of his textiles. After his experience using Ardil in History of Shapes, he continued to work with ICI, producing several commercial ranges of fabrics using Ardil (Figure 6a). Tibor's typical yarn palette would include wool yarns in different specifications, combined with viscose and Lurex wefts woven on a cotton warp. Ardil blended well with all of these fibres, and would have been complimentary to his existing products. Designs produced by Tibor Ltd. in Ardil included the Jacquards *Movemento*, *Granite*, and *Gazelle*, as well as power-woven designs, including Ardil Prince, Henley, and one of Tibor's most popular designs, California. Tibor was so taken with Ardil that he created a distinctive design celebrating peanuts, entitled Harvest (Figure 6b). Using the unusual technique that he had developed with History of Shapes, Harvest has a woven Jacquard background, which it was screen-printed onto. The motifs in the design are based on the process of harvesting peanuts. Tibor produced a similar design, called "Aluminium story", depicting the process of smelting aluminium [56].

Many other important names from 20th century textile design were keen to develop products using Ardil fibres. During the course of this research, it was discovered that one of the most notable manufacturers of 20th century textiles, Warner & Sons, also worked with Ardil fibre. Warner & Sons' power-woven record books show an Ardil fabric being produced in 1953 (Figure 7). The piece described in the log was produced for ICI in February 1953, suggesting that the intention was to showcase it on the Ardil stand at the BIF. The

fabric was described as being green in colour and made form a blend of Ardil and silk. Further research is required to determine whether the Warner Textile Archive still holds any examples of this Ardil fabric. Other noted designers who lent their signature designs to Ardil fabrics included Jaqueline Groag, John Piper, Lucienne Day, and the sculptor Nicholas Vergette [57].

Figure 6. (**a**) "Tibor weaves new 'Ardil' blend textures" advert circa 1954. (**b**) Furnishing fabric, Harvest, depicting the process of harvesting peanuts, designed by Tibor Reich, Stratford-upon-Avon, circa 1953.

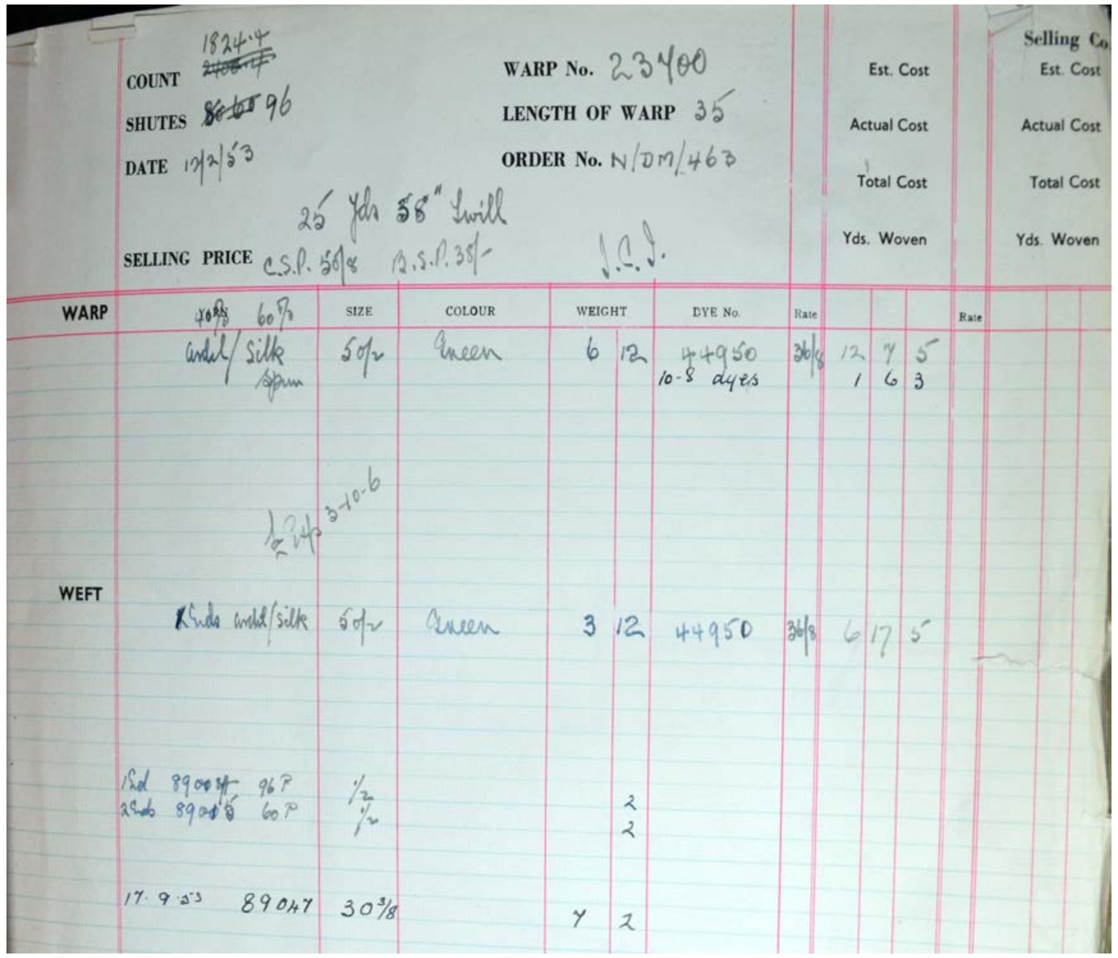

Figure 7. Power-woven fabric ledger, Warner & Sons, Warner Textile Archive, 1953. Reproduced with permission from the Warner Textile Archive, Braintree District Museum Trust.

3.4. Political and Economic Factors

Put simply, there are four main political and economic factors that governed the development of Ardil and can help to explain why it failed. These were the Second World War, the price of wool, the supply of peanuts, and the rise of petrochemical fibres. Whilst all of these are interlinked, each subject is tackled independently here to help understand the picture as a whole.

3.4.1. The Second World War

Although the Second World War was beneficial for development of many RPFs—most notably in Italy—the war actually postponed further development of Ardil, as much of ICI's technology was diverted towards the war effort. In fact, ICI's Drungans site in Dumfries, which would later become the Ardil plant, was originally created by ICI to produce munitions [58]. The peanut meal used to create Ardil was needed to supplement food supplies [39]. This significantly delayed the material developmental progress of Ardil. In contrast to the UK's postponement of Ardil, Italy doubled down on their output of RPFs during the war, clothing their army in Lanital uniforms. This may be in part due to the development of Ardil being several years behind that of Lanital; at the outbreak of war in 1939, Ardil was still only a lab creation. In 1944, development work on Ardil resumed, although ICI were still not able to produce Ardil in large quantities. "When the war ended, a small pilot plant was built and sufficient 'Ardil' produced to enable us to form some idea of its commercial possibilities" [42]. Slow development did not stop the press from eagerly reporting a 1944 press release from ICI. An article in *The Draper's Organiser* from January 1945 announced "New Wool-like Yarn from Nuts ... ICI's important contribution to synthetic fibres" [18].

3.4.2. The Wool Price

The war impacted the supply of raw materials, and there was a notable strain on wool supplies. At first, this was promising for Ardil and other RPFs, as it indicated that wool stocks could not be solely relied upon to keep up with demand for clothing [59]. Even the wool industry felt that scientific enhancement would likely play a part in the future of wool [60]. When wool prices began to climb to their most expensive in history at the end of the 1940s, it is likely ICI felt vindicated in their decision to invest to so heavily in Ardil. The cost of wool reached the highest it had ever been at "$125\frac{1}{2}$ d. per lb. on 26 January 1951" [61], roughly equivalent to GBP 41.80 per kg in today's money [62,63]. This steep elevation in price was caused by the government commandeering the British Wool Clip during the war. They continued to pay a set price for wool based on a pre-war price. This price did not reflect the cost of sheep farming and wool production at the time, so when the price cap was lifted at the end of the war the cost of wool rose significantly [64]. The demand for wool during the war period was also steadily increasing while the global output of wool fell, further inflating the price [65,66].

Data gathered compiled using Kreglinger and Fernau market reports shows the prices for wool at the London sales between 1924 and 1954 (Figure 8) [66], demonstrating the lack of recorded prices during the war period and subsequent elevation in price post-war. Unfortunately for ICI, this seemingly exponential rise in the price of wool did not last. The drop in wool prices globally [67] from 1951 onwards doubtless took a toll on Ardil, as industry partners were not as likely to try a more expensive, unfamiliar fibre over a reliable material such as wool. The commercial success of their product relied upon the price being highly competitive compared to wool and other fibres.

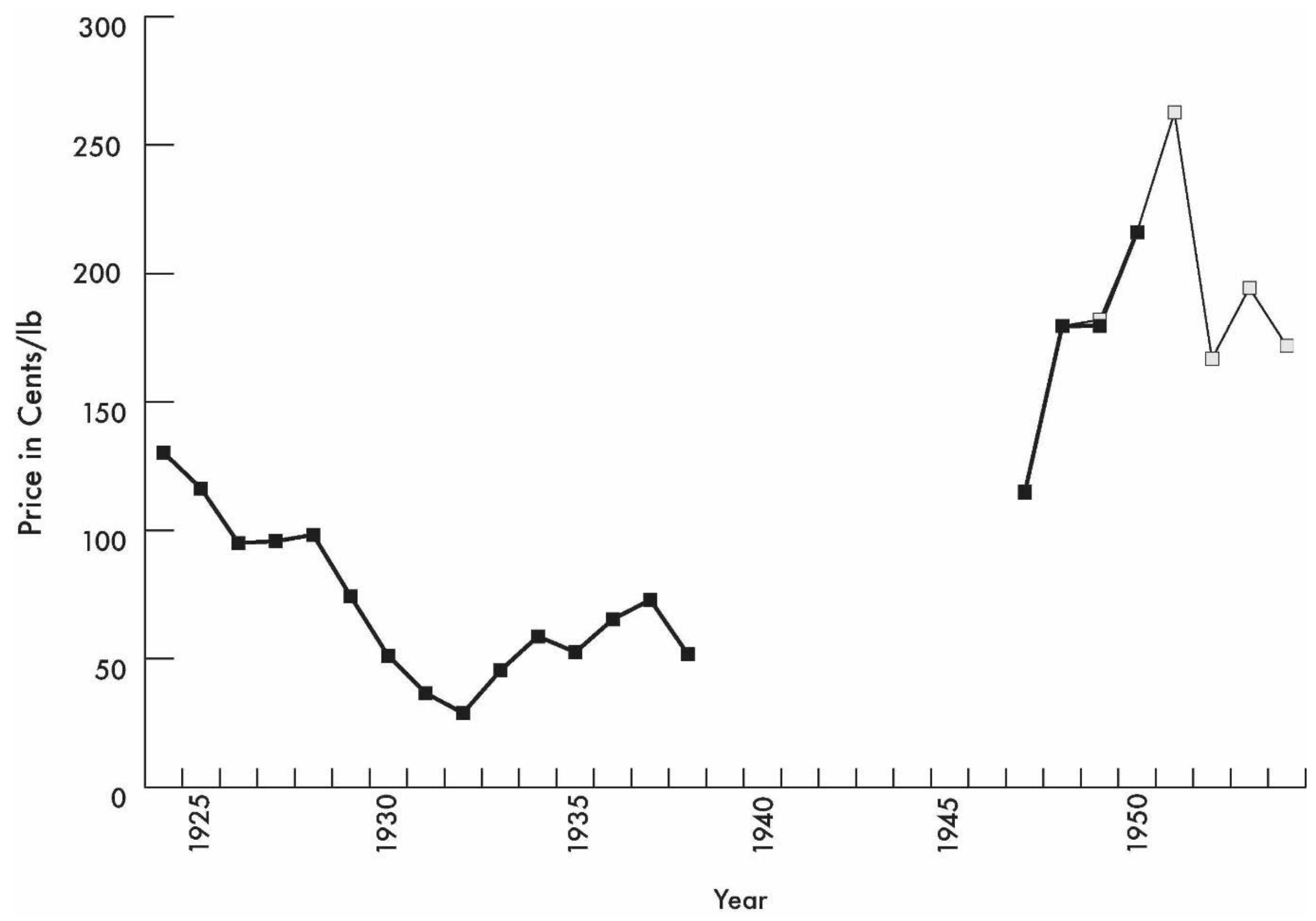

Figure 8. Graph showing the absence of a wool price during the war, and the initial spike and subsequent drop-off in wool prices post-war. Average price per pound and price differentials of fine wool at Boston and London markets, 1924–1954. N.B., Data taken from two separate sets, indicated by the colour change on the graph. Wool can be a difficult commodity to price, as it varies so much in quality, and is subject to fluctuations in yield. Data on the production and price of wool are therefore complicated to extrapolate, but the datasets used reflect the market trend as whole.

3.4.3. Supply of Peanuts

ICI had also not considered the difficulties they would face in finding the raw materials needed to scale up their production. At the same time as the peak in wool prices (July 1951), W Johnston at ICI wrote to Mr Greenhill of the Trades and Marketing Department of the Colonial Office, stating that he "would very much welcome any help or guidance which the Colonial office can give us in finding a source of consistent supply of good quality groundnuts ... to be used for the production of Ardil Protein Fibre" [68]. The problems ICI were experiencing came from the quality of protein yielded from the peanuts. They had already experimented with several varieties of peanut, each giving different results; the quality of the fibre produced was closely linked to the quality of the protein that could be extracted from the peanut meal [68]. As such, ICI found that they had to be highly selective about the peanut meal they used for the development of their product, forcing them to seek more reliable and consistent sources whilst narrowing their options. Johnston had contacted the Colonial Office off the back of a report about the available protein supplies for Ardil published by the Ministry of Food [69]; the report expressed concern about the growing demand for peanut meal from the textile industry, and warned that this demand had already come at the expense of "feeding-stuffs supplies" [69].

3.4.4. East Africa Groundnut Scheme

The failure of the East African Groundnut Scheme (EAGS) was also making headlines in 1951. Started in 1947, the EAGS was a proposed solution to post-war food shortages. The scheme entailed cultivating large quantities of peanuts in the shrubland of Tanganyika, now known as Tanzania [70]. It would be easy to assume a causal link between the demise of the EAGS and the demise of Ardil, but a direct link between the two is not clear [42]. The work on developing Ardil had begun long before the conception of the EAGS; concurrently, the EAGS was developed as a response to food shortages, not textile shortages. Correspondence from ICI shows that they were working with peanuts sourced from around the world, including India and China, as well as several other African countries in addition to Tanzania [70]. There is further correspondence showing an interest from ICI in the progress of the EAGS in early 1952 [71], but the demise of the EAGS was already in motion [72]. Instead, it would be more accurate to suggest that the simultaneous rise and fall of both Ardil and the EAGS speak to the wider trend of peanuts as a commodity at the time, and the promise that they held as both a fibre resource and a foodstuff.

3.4.5. The Rise of Petrochemicals

As referenced in Figure 1, the development of Ardil and other regenerated protein fibres coincided with the development of new fibres from the petrochemical industry. The synchronicity of these emerging fibre technologies is perfectly encapsulated by ICI itself; at the same time as they were working on Ardil, they were developing another patented textile fibre—Terylene. Terylene is the ICI brand name for polyethylene terephthalate (PET)—a fibre derived from petrochemicals. These two textile products from ICI were developed concurrently; the 1953 BIF also served as a launch pad for Terylene, with one side of the dual-aspect stand being used for each fibre. While the Ardil factory at Ardeer was being built, a pilot plant was producing Terylene in Lancashire. A full-scale production facility dedicated to Terylene was completed at the end of 1954. It was capable of producing up to 10,000 tonnes of fibre a year, and was situated in Wilton, in what is now Teesside [73]. ICI invested heavily in and widely promoted both products; however, Terylene ultimately won, succinctly summarised by this 1957 headline in *The Outfitter* "Terylene output to be doubled—but it's the end of Ardil" [74].

4. Discussion

Ardil represents a unique and important case study in the development of RPFs. Its lifespan only lasted 22 years from conception to demise, but during that time Ardil was hugely prevalent. From the first experiments carried out by Astbury in his lab at the University of Leeds to the practically overnight closure of the Ardil factory in 1957, Ardil's story is full of Hollywood-like twists. The huge amounts of finance and time invested show how strongly Ardil's backers believed that this could be the future of material science. At its best, Ardil was a fibre that could simplify manufacturing techniques, address material shortages, and provide consistent and superior textile qualities such as drape and lustre. At its worst, Ardil was an expensive experiment that produced inconsistent results, was not scalable, could never be price-competitive with equivalent fibres such as wool, and lacked material longevity.

Unfortunately, the popularity and success of petrochemical textiles meant that RPFs were largely abandoned, and much of the information and research into them became obscured. In the 21st century, we are seeing a huge reversal in the popularity of petrochemical fibres as we discover more about their detrimental impact to the planet. Had we known then what we know now, research into RPFs might not have died out in favour of petrochemical fibres. RPFs hold huge potential for the future of sustainable textiles. A vast quantity of research into this field already exists, but is currently inaccessible for researchers wishing to build upon it. Archival research has provided more detail and clarity as to the reasons why Ardil failed, uncovering previously unseen or little-known material that has helped to build a clearer picture of the history of this once-celebrated fibre.

This methodology of reflecting on lessons from societies past has been mentioned by the Centre for Circular Design, Chelsea College of Arts, as part of their TED's TEN toolkit for sustainable design [75].

Ardil is a prime example of how and why RPFs met their untimely end as a result of myriad factors. Perhaps the most important of these was the poor performance of these fibres in comparison to others available on the market. It was clear that manufacturers were not always as keen to work with these new manmade fibres as the companies who promoted them. Another 1957 article in *The Outfitter* entitled "Test fibres for longer before we sell them" described how manmade fibres had "bedevilled the outfitting trade since the war" [76]. Customers were also not as keen to buy Ardil as ICI had hoped, with sales failing to grow. The struggle for new and experimental fibres to be accepted into a wider market is an important lesson to be taken forward into contemporary RPF development; the inherent poor fibre strength that plagued manufacturers at the time could now be seen as an opportunity, aligning RPFs with alternative, faster fashion cycles [77].

The issues Ardil faced with the supply of the peanut raw material are also relevant to contemporary RPF research. After the end of the hostilities in WW2 and the subsequent dissolving of the British Empire, the volume of peanuts imported to the UK reduced massively, meaning that the economics of utilising peanut waste for textile manufacturing were no longer favourable. While it was also hoped that Ardil would be cheap to manufacture, as it largely utilised byproducts from the food industry, it became clear that ICI needed to be more selective with the proteins they used in order to produce the best-quality fibre. Therefore, they began to move towards sourcing peanuts directly for producing Ardil, which was far less cost-effective than using peanut waste as they had initially planned. This highlights the need for robust future-proofing when designing a circular economy, ensuring that feedstocks are ideally locally sourced as well as actual waste streams.

Looking into the future of incorporating regenerated protein fibres into a circular economy, the environmental impact of the production process in terms of both the chemicals used and the volume of water consumed has to be considered; there has been a lot of contemporary research done into the replacement of formaldehyde as a crosslinking agent with more sustainable options, such as polycarboxylic acids; and methods for regenerating the water used within the process to try and "close the loop" could help alleviate issues with excessive water consumption. More research would have to be performed to determine the full environmental impact of these fibres through LCA, to identify which areas need to be improved and how they could be improved from an environmental perspective.

5. Conclusions

From a modern sustainability perspective, the prospect of importing vast quantities of produce from overseas is also problematic, with the correspondingly large environmental impact of transportation of the goods. It is much more attractive to look at processing the feedstock at a local level and utilising the waste as close to the production and processing as possible. Within the UK, there is no longer any potential for utilisation of large quantities of peanut waste, but the UK does have other forms of protein waste that could potentially be utilised. The majority of food consumed within the UK is actually dairy, accounting for roughly 27% of the food eaten [78]; therefore, a correspondingly large volume of waste is generated, with over 330,000 tonnes of milk being wasted every year, giving potential for RPFs from milk—such as casein fibres—to be explored. However, it should be noted that the majority of the milk being wasted in the UK is being generated in homes (90%), which would give rise to logistical problems for collection and ensuring that a uniform feedstock is obtained [79]. Casein-based RPFs were pioneered within Europe at roughly the same time as Ardil, with fibres such as Lanital having a similarly short-lived lifetime during and after WW2, although more contemporary research has been conducted into casein-based fibres [77].

While the demise of the UK-based RPF Ardil was marked by the sudden lack of peanuts being exported into England, this does not represent a reduction in the peanut waste being generated globally. Indeed, peanut production has seen a marked increase in recent years, due to an increase in the popularity of peanut oil. Global peanut production has increased from 31.4 Mt in 2000 to 48.1 Mt in the 2019/2020 season, representing a > 50% increase in the last 20 years [80]. Global peanut oil production has increased from 4.5 Mt in 2000 to 6.5 Mt in 2021/2022, representing a roughly 43% increase [81]. When processing peanuts for oil, the waste in the form of peanut meal can be as high as 70%; the global production of peanut meal in 2019–2020 was 7.7 Mt. As discussed previously, this peanut meal has a 53.3% average protein content, representing a raw waste protein mass of roughly 4.1 Mt; currently, the main use of this feedstock is animal feed. However, this is a low-value valorisation route for this waste feedstock, and also poses potential issues with contamination with aflatoxins. Peanuts are particularly susceptible to contamination by *Aspergillus flavus* and *Aspergillus parasiticus* fungi, which produce aflatoxins that in high enough doses are lethal to both humans and animals, and low doses can still cause myriad diseases, including cancer in humans, and have been shown to reduce weight gain and milk and egg production, as well as causing contamination of milk in animals. These issues do not stop peanut meal being a highly effective animal feed component, but they do highlight that it is not a perfect solution to this waste stream, and there is historical precedent to allow for this huge waste stream to help alleviate the modern world's reliance on non-renewable textiles [82].

For both of the feedstocks discussed, as well any waste utilised with the intention of replacing conventional fibres in the textile industry, care must be taken regarding the volumes of feedstock required. The textile industry is huge, and if regenerated protein fibres were to be accepted as a replacement for non-renewable fibres, the feedstock would need to be able to keep up with demand. This issue would require a collaborative effort across multiple disciplines to determine whether replacement with RPFs would be feasible, with potential future work being focused on the opportunities and drawbacks for theses fibres through SWOT analysis and LCA. It would also be important to learn from past mistakes and use the critical analysis of why Ardil failed during its initial conception, and what factors could be used to avoid such failure in the future.

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10.6.4 Paper 4: Challenging Perceptions Of Fast and Slow In Contemporary Fashion: A Review Of The Paper Dresses Trend In The United States During The 1960s

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Challenging perceptions of fast and slow in contemporary fashion: A review of the paper dresses trend in the United Kingdom and the United States during the 1960s

ABSTRACT

Writing in 2022 we are at a global crisis point, as our use of the planet's finite resources outstrips supply. Our current lifestyles continue to perpetuate this problem by encouraging excessive and wasteful models of consumption. One of the most detrimental industries for this is the clothing industry. Our fashion cycle

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is now programmed to be 'ultra-fast', encouraging excessive consumption of garments causing myriad environmental issues. This article argues that there are developing models of both manufacture and consumption, which can satiate this need for 'fast' fashion whilst being part of the wider sustainable fashion conversation. Rather than understanding the short-term life cycle of clothing as inherently unsustainable, this can be reframed as matching a garment's use phase to the longevity of the material it is made from. This article uses a material culture approach to explore original 1960s paper garments, alongside a critical analysis of the sustainability of their manufacture and disposal from a green chemical perspective. Using the combined knowledge and experience of its authors, from historians and sustainable fashion designers to green chemists and biochemical engineers, this article demonstrates how such garments could inspire new models of sustainable fashion production and consumption. We argue that the current paradigm of slow fashion as the only antidote to fast fashion must be challenged. Instead, the fashion and textile sector must consider a range of solutions to the environmental burden of fast fashion that are human-centred and sympathetic to all consumer demographics and needs.

INTRODUCTION

In 2022 climate breakdown has become a frightening reality, accelerated by our usage of the planet's finite resources. Excessive and wasteful models of consumption dominate internationally, and the clothing industry is amongst the most damaging. New solutions are needed to try and balance the demand for clothing.

Using the paper dress phenomenon of the 1960s as an early exemplar of fast fashion can help us explore potential solutions. At its core this trend offered a cheap material with which to make clothing that could then be easily discarded after use. A precursor to fast fashion as it might be understood today, these dresses offered high fashion at a low price, allowing consumers to frequently update their wardrobes. However, these dresses were arguably flawed – difficult to wear and incapable of being recycled due to the use of mixed fibres. Though these paper garments are regularly dismissed as a fashion fad, fads are often a manifestation of potent philosophies and ideologies and therefore still worthy of consideration (Palmer 1991: 85–104). Whilst paper dresses were not designed for circularity, we can draw important information about material properties and user experience from these historical garments. This technique of reusing and reinterpreting historical models of design to inform sustainable systems is recognized by the Centre for Circular Design as a way to approach sustainability (The TEN n.d.).

Fashion's speedometer is now set to 'ultra-fast'. Between 2000 and 2015, fuelled by fast fashion, social media and online e-commerce platforms, clothing production doubled (Ellen MacArthur Foundation 2017: 36). Furthermore, the number of fashion seasons has increased dramatically (Bhardwaj and Fairhurst 2010: 167). A 2019 Swedish study of clothing consumption determined that nearly 80 per cent of climate impact happens during the production phase, highlighting the harm created purely by increased demand (Sandin et al. 2019: 70). In response, there have been increasing calls for 'slow fashion' models of production and consumption, where clothes are valued and kept in circulation for longer.

'Good On You', a leading source for brand ratings, articles and expertise on ethical and sustainable fashion, defines slow fashion as encompassing an awareness of fashion that considers the processes and resources required to make clothing. This outlook advocates buying better-quality, long-lasting garments and values fair treatment of people, animals and the planet (Good On You 2021). Similarly, campaigns such as 'Love Your Clothes' (Love Your Clothes n.d.) and 'Love Not Landfill' (Love Not Landfill n.d.) aim to provide consumers with tools to care for their existing clothing longer. However, there are drawbacks to slow fashion, such as price point; slow fashion can be unattainably expensive, with consumers of slow fashion willing to accept a '30 to 40 percent price premium' (Štefko and Steffek 2018: 3). Affordability coupled with quickly changing trends and a consumer desire for new garments means that a universal adoption of slow fashion is unlikely in the short to medium term.

The basic definition of slow fashion tends to ignore the complexities of garment use and is therefore not appropriate for all garments. Though we often require different lifespans from our garments, there is currently a lack of viable routes for disposal. A 2017 report estimated that out of 53 million tonnes of fibre produced annually, 73 per cent will end up either in landfill or incinerated (Ellen MacArthur Foundation 2017: 20). Prioritizing longevity in textiles means we ignore the potential detriment of that longevity.

Such a complex problem cannot be simplistically divided into good and bad models for sustainability; instead our approach must be more refined. Herein, we argue that there are alternative models of manufacture and consumption, which can satiate the desire for fast fashion whilst also engaging in the wider sustainable fashion conversation. Rather than understanding the short-term life cycle of clothing as unsustainable, this can be reframed as matching a garment's use phase to the longevity of the material it is made from.

METHODOLOGY

This article takes an integrative cross-sector approach to explore – through the lens of fashion history, fashion and textile design and green chemistry – the potential for the paper dress to be used as a framework for a new and novel solution to the environmental burden of fast fashion. This builds upon the technique of re-examining historical models of design to inform sustainable systems proposed by the Centre for Circular Design (The TEN n.d.). The brief trend between 1966 and 1968 for paper dress forms the basis of this case study. The authors analyse paper dresses against three main criteria – manufacture and construction; consumer experience; and end of life – to better understand the life cycle of these garments and how they might inform a circular economic model for textiles. Combining research from archives, newspapers and magazine articles, contemporary journal articles and object analysis, the authors argue that new models of fast fashion can develop that are human-centred, sustainable and sympathetic to consumer demographics and needs.

1. MANUFACTURE AND CONSTRUCTION

Whilst 1960s disposable dresses were referred to as 'paper', they were not what we traditionally think of as paper but instead made from a variety of cellulose-based materials. For clarity we will hereafter describe this as 'paper material'. Paper materials lie somewhere between fabric and conventional

1. At this time newspapers and journals use the terms rayon and viscose interchangeably to describe the scrim, although primarily, in Britain, it was described as rayon.

paper – combining textiles fibres with techniques utilized in paper manufacture to create a non-woven material (Wilson 1967: 16–17). Typically, these textile fibres, primarily cellulose, were pulped and calendared into sheets or rolls that could be easily printed (Anon. 1967c: 8). Often the paper was bonded with glue or coated in plastic to make it water-repellent and fire-retardant (Anon. 1967g: 9). Even at the height of its popularity there was consumer confusion surrounding paper materials. A 1967 article called for a 'proper definition' of paper so that consumers had a clear understanding of 'what to expect in terms of wear and what to pay in consequence' (Anon. 1967c: 8).

1.1 Paper material makers

Several types of paper material were used for garments in the 1960s; however, the most popular was made from a paper or cellulose pulp, strengthened with a layer of nylon or rayon scrim.[1] This paper material was cheap to produce, and in Britain the wholesale price was around 1*s* per yard for plain fabric, or 2*s* per yard for printed (Anon. 1967c: 8). Both the paper and textiles industries produced variations of paper material (Lippall 1967: 55).

The United States was an advanced producer of paper materials for fashion garments with several companies recognizing the potential for high-volume sales. Scott Paper Co. was one of the earliest firms to manufacture paper dresses on a mass scale, selling 500,000 dresses at $1 each (plus $0.25 handling) during 1966. Their dresses were made from 'Duraweave', a three-ply paper reinforced with rayon scrim. Despite the success of these garments, Scott Paper Co. regarded them simply as a marketing ploy, designed to encourage purchase of their other disposable paper products (Anon. 1966a: 8).

Kaycel, produced by Kimberley-Stevens, was amongst the most common paper materials used by firms, made from a blend of 93 per cent cellulose and 7 per cent nylon. This material was fire-resistant, unless washed, which would remove the finish (Met Museum 1986.91.7a–c). Mars of Asheville, North Carolina, one of the most prolific paper dress firms, used Kaycel for their garments. Unlike Scott Paper Co, Mars were already garment manufacturers, specializing in hosiery and swimwear. They identified a gap in the market and turned their production lines over to paper garments, ranging from basic A-line shift dresses (retailing at $1.29) to evening gowns ($5) and even bell-bottom jumpsuits ($4) (Goodman 1966: 31). Examination of a Mars dress (as well as a paper dress by the designer Elisa Daggs) at the Metropolitan Museum of Art, New York, clearly shows the nylon content of the Kaycel material in the form of a scrim layer running through it, giving a distinctive grid-like structure (Figure 1). Mars worked closely with American department stores, and their 'Wastebasket Boutiques' were added as concessions to stores including Abraham & Strauss and B Altman's in New York (Shepard 1967: 4–5, 34). In 1966 it was reported that Mars were selling 80,000 paper dresses a week (Goodman 1966: 31).

1.2 Paper material qualities

The nylon or rayon scrim layer running through paper materials helped to ensure they behaved more like traditional textiles. Many accounts indicated that paper garments were strong, durable and not prone to tearing (Anon. 1966b: 38–39).

Figure 1: Elisa Daggs, Evening Dress*, 1967. The Metropolitan Museum of Art, New York. Author's photograph.*

Paper materials took colour extremely well and garments were often printed with exuberant op or pop art patterns in vibrantly saturated colours. For example, a 1967 advertisement for *Petticoat* magazine's paper dresses described the colours available as 'crazy pink and orange candy or glowing lime and mauve combo' (Anon. 1967d: 11). Manufacturers exploited the boxy silhouettes of paper dresses, using them as canvases to print large abstract or photo-realist prints and even political campaigns. Amongst the most striking were those manufactured by Harry Gordon; his poster dresses included an overblown eye design, 'mystic eye', which was printed boldly across the dress.

Object analysis conducted by the authors in 2022 indicated that paper dresses produced between 1966 and 1968 were primarily printed using water-based formulations. This is hypothesized because the designs appear quite flat and the fibre structures are generally visible under the printed sections, which other printing methods would obscure (Merritt 2022: n.pag.). Water-based inks are typically made up of acrylic resins or polyurethanes in water, commonly with a volatile co-solvent to reduce drying time. Some contained formaldehyde to aid in pigment binding. These dyes could be cured at relatively low temperatures (Ukena 2005: 8–11; Kiurski et al. 2012: 18–25).

The crisp A-line silhouette of most paper dresses was central to their appeal. Whilst paper material was ideal for creating such silhouettes, the potential flammability of paper was concerning to retailers and consumers. Generally paper materials were treated with flame-retardants which would have slowed the flame spread. However, washing did typically remove these coatings, but as the consumer was forewarned of this on the label and the garments were designed for short-term use only, this was deemed acceptable (Anon. 1967a: 9).

It cannot be ascertained what flame-retardant finish was used on paper materials; however, due to their cellulosic nature, it is likely that flame-retardants designed for use on cotton were employed (Horrocks et al. 2005: 3–12). There were a host of flame-retardants developed for use on cellulose in this period, but given the warnings about laundering of the garments leading to removal of the flame-retardant coating, it is likely that one of the following methods was used:

- The binding of phosphoric acid to cellulose via esterification using formaldehyde and stabilized by either urea or titanium salts. This method results in a hydrolytically unstable P-O bond with reduced resistance to washing.
- Application of an inorganic salt, such as titanium or antimony salts, to the surface of the cellulose, creating a non-durable or semi-durable flame-retardant coating.

Both are environmentally concerning on a process and disposal level. Formaldehyde is a toxic, volatile compound that causes serious health issues for manufacturers and consumers. Metals such as titanium and antimony, if leached into groundwater via laundering or disposal, have the potential to endanger aquatic life (Horrocks 1986: 62–101).

1.3 Garment construction

The rise of paper dresses must be understood as part of wider fashion trends of the 1960s. Increasingly there was a desire for simpler silhouettes, and less layers of underpinnings – such as corsets and petticoats – to give garments structure. Internationally, designers were creating bold garments that no longer necessarily followed the contours of the body. Novel paper materials provided excellent scope for experimentation. Between 1966 and 1968 a wide variety of paper dresses were produced – ranging from simple creations made with just two pattern pieces to elaborate designs more akin with haute couture.

Most paper dresses were sleeveless, produced in limited size ranges (sometimes just small and large) and were designed as simple A-line mini shifts, tent shapes or baby smock styles. The dresses were typically left un-hemmed as paper material does not fray. Garments were assembled in various ways; most surviving examples have stitched seams, but articles indicate that some were bonded or even sellotaped together (Murgatroyd 1967: 1; Anon. 1967a: 12). Paper dresses tended not to have fastenings and were designed to slip over the head, with necklines cut relatively wide to allow for this. These design decisions helped to keep manufacturing costs low, both in terms of amount of material used and the need for skilled or time-consuming labour in production. Consequently, this meant that paper dresses could be retailed at low prices.

Surviving examples of paper garments, such as a 'Paperdelic' dress at the Met (Met Museum 1994.468 – Figure 2), illustrate the simplistic construction

methods generally used. This garment has a basic batwing silhouette, avoiding the need for shaping through darting. The stitching is poorly executed and looks rushed, and unlike some other paper dresses viewed, it has not been overlocked. On the other hand, Scott Paper Dresses, amongst the cheapest available, had relatively complex and detailed finishing (Met Museum 1995.444.1). These dresses had features including pockets and facings and used bias binding on the armholes. The overall design was still relatively simplistic, consisting of two main pattern pieces and a raw hem, but the execution was of a high standard.

Garment construction was also sometimes left to the consumer, and paper dresses were offered as flat pattern pieces for the home seamstress. *Petticoat* magazine, for example, offered a paper dress 'ready cut-out'

Figure 2: Paperdelic, Dress, *1965–75. The Metropolitan Museum of Art, New York. Author's photograph.*

– designed to be sewn at home 'in a matter of minutes' (Anon. 1967a: 11). These were more complex than many of the commercially available paper dresses, sent with matching bias binding and utilizing at least three pattern pieces. Advertisements and editorials for paper dresses highlighted the 'at home' customization opportunities, allowing consumers to effectively become designers themselves. Paper material could easily be cut into interesting shapes as it did not fray. An advertisement for Ac'cent paper dresses suggested that they could be 'scissored any way you want … maxi, micro, slanted' (Anon. 1967b: 35–37). A 1968 editorial featuring Nescafe dresses went even further, suggesting that one could 'cut the hemline into scallops or a fringe, or make an openwork pattern of diamonds or flowers, or cut midriff holes front and back' (Anon. 1968: 12).

In contrast to this, some designers created elaborate garments from paper, recognizing that its low cost offered scope for experimentation. Judith Brewer's Kaycel garments typically retailed between $10 to $40; however, she also offered extravagant garments including custom-cut 'fur' coats made of shredded paper priced at $200 from her boutique in Beverly Hills, California (Carlton 1966: 130–36). From a construction perspective, American designer Elisa Daggs' paper garments are amongst the most complex, utilizing multiple pattern pieces to create striking silhouettes. Daggs created a variety of paper garments including striped kaftans (retailing at $7), specially treated raincoats ($7.50) and even bikinis ($4) that could be worn in water two or three times (Goodman 1966: 31). One of her most complex garments was a rainbow-striped paper sun dress comprised of eight pattern pieces (Met Museum 1986.91.6 – Figure 3). The design relies on aligning print to accentuate the line of the dress, a time-consuming design choice. Palmer notes that unlike other designers of paper garments who exploited the natural qualities of paper, Daggs approached designing with the material as if it were 'a cloth dress […] [with] little care for its transience' (Palmer 1991: 91).

As we have illustrated, the construction methods associated with paper dresses were often in contrast with their short-lived existence. This can still be seen today, whereby time-consuming manufacturing processes are used for 'low cost' items. Many garments and the fibres used to make these garments have a potential lifespan that 'far outweighs their short fashionable life' (Stanes and Gibson 2017: 27). This concept of mismatched speed cycles has previously been explored in various papers (see Goldsworthy et al. 2019; Stenton et al. 2021a, 2021b).

Kate Fletcher, who has written extensively on slow fashion, has suggested that the terms 'fast' and 'slow' fashion are misnomers that generally refer to the economic models of consumption rather than the garment itself; the processes involved in producing the fibres and garments still take the same amount of time; it is the delivery and consumption that is sped up or slowed down (Fletcher 2007: 189–218). The concept of slow fashion, as outlined by Fletcher, focuses on alterations at a systems level to the way we interact with, value and use clothing and not as a subvariant of the traditional model of high consumption and waste (2010: 259–65). Fletcher concludes that instead of the antidote to fast fashion, slow fashion and fast fashion are in fact complimentary (2012: 124–30). In considering this outlook of fast and slow when assessing the techniques used in paper dresses, there are lessons to be learnt from their construction such as bonding rather than stitching seams. This contributes to the reduction in time, energy and resources required to construct garments, ultimately leaning towards a more matched speed cycle.

Figure 3: Elisa Daggs, Evening Dress, *1967. The Metropolitan Museum of Art, New York. Courtesy of the Metropolitan Museum of Art/Art Resource/Scala, Florence.*

2. CONSUMER EXPERIENCE

Paper dresses were the epitome of a new direction in fashion – on the whole these were lost-cost items – designed to appeal to the increasingly affluent teenage market who were spending their disposable income on clothes, music and their social lives. They were generally seen as a garment reserved for 'fun' occasions where one might desire to wear something new. This is suggested in the wording of advertisements – an advertisement for Wall's ice cream paper dresses described them as 'the raviest ever! Guaranteed to steal party scenes!' (Anon. 1967b: 11). Increases in pay alongside annual leave given to British workers in the 1960s led to new opportunities for middle- and working-class people to travel internationally. Paper dresses were the ideal item to take on holiday, taking up very little room in a suitcase, and disposable before return.

There was no incentive to wash paper garments as their cost was less than laundering similar garments made from cotton or synthetic fibres (Smith 1968: 24). The popularity boom in paper dresses highlights the importance of matching design and manufacture process to consumer wants and desires.

Paper dresses should be understood as part of a broader change in fashion whereby there was an increasing demand for inexpensive clothing, produced quickly to meet ever-emerging new trends. Young adults were both the designers and consumers of much of this low-cost fashion, and their influence was seen across the industry (Scott James 1960: 6). Young consumers were seen to have a fickle attitude to fashion. As an *Irish Times* article suggested, they did not 'wear dresses more than a few times' before discarding them (Anon. 1966a: 6). The move towards disposability suggests not only a desire for perpetual 'newness' but also the decreasing material value of clothes. Many consumers were not seeking out 'quality' garments which were made to last, and aesthetic value trumped material value.

2.1 Experiencing British paper dresses

In 1961 British designer Teddy Tinling, already well known for his tennis dresses, produced a range of tennis fashions in paper. The dresses were made from paper mounted on a nylon lattice work, imported from America (Anon. 1961: 6). Despite Tinling's early experimentation, British consumers were slow to adopt paper dresses. Ossie Clark launched a dress made from Ascher paper material, printed with a floral design by Celia Birtwell, in December 1966. The first dress retailed at just 17*s* and 6*d*, and early in 1967 he launched a range of twelve different paper dresses, none costing more than £1 (Lowe 1967: 15).

Mornessa, until the mid-1960s a coat and suit specialist brand targeted primarily at the middle-aged consumer, pivoted and produced some of the most striking paper dresses as part of their 'Marcus boutique range'. These dresses were designed by Paco Rabanne and made from Vilbond. This paper material had a crinkly texture, was non-rustling, soft to the touch, flame-proof and had been tested for stress. The Mornessa dresses were not sewn. Seams were joined by a strong bonding process, and each was expected to last two or three wears (Thomas 1966: 3). This range included evening, cocktail and day dresses and fashion overalls, retailing at between 7*s* 6*d* and 25*s*. Rabanne's designs were particularly bold, and some garments were appliqued with paper and plastic discs (Hackett 1967: 7).

Dispo, established by Diane Meyersohn & Joanne Silverstein, was a popular British disposable dress brand. One particularly bold garment they produced was inspired by Art Nouveau designs seen at the Victoria and Albert Museum. This dress, costing 22*s* and 6*d*, was widely promoted in the fashion press and appeared in a 1967 *Rave* editorial in three colours – pink and orange, lime and pink, and green with turquoise (Figure 4) (Anon. 1967f: 4–5). The paper material used in these dresses was a type of Vilene, produced by Bondina Ltd., a company formed by Bradford Dyers' Association in 1956 to produce non-woven fabrics. Different to many American examples that used a supporting rayon mesh structure, Vilene has a random fibre structure which can be seen on the reverse of the fabric. It should be noted that Bondina made fabrics under license from German company Carl Freudenberg. Freudenberg initially experimented with creating a leather substitute before turning to create interlinings for garments (Welling 1962: 17). For the paper consumer,

Figure 4: Dispo (Meyersohn & Silverstein Ltd), Art Nouveau Dress, *1967. The Victoria and Albert Museum, London. © Meyersohn & Silverstein. All rights reserved, DACS 2022.*

Vilene had advantages over other paper materials – and was able to be washed several times.

2.2 Target markets and retail

The visual merchandising of paper dresses in department stores highlighted their fun and even gimmicky nature. For example, in America, B Altman's 'Wastebasket boutique' took a 'light-hearted carefree attitude' with four large round tables covered in brightly coloured felt standing in front of large New York City sanitation department wastebaskets. Paper dresses hung from hangers attached to the wastebaskets (Shepard 1967: 4–5, 34). In Britain there is less evidence of how paper dresses were retailed and the associated visual merchandising. Several articles suggest that store buyers were 'cautious' of them, even stores well known for supporting young designers and the latest trends, like Fenwick's in London (Ashdown-Sharp 1967: 4). However, Peter

Robinson's 'Top Shop' in Oxford Circus certainly stocked paper dresses, as did Harrod's 'Way-In' department, which opened in 1967. One journalist, who visited during its opening week, provided a detailed description of this space, which points to how stores, particularly department stores, were trying to entice new, younger consumers.

> Beat music throbs through the midnight blue atmosphere – walls and low ceilings are painted blue, low chunky seats […] are covered in the same shade of blue. Dimly, because it's all mixed up amongst the merchandise, I noticed that a coffee bar was being well patronized. Gear for both sexes is also mashed together.
>
> (Curry 1967: 6)

Paper dresses represented a new dichotomy in fashion – a high-fashion item sold in boutiques and simultaneously given away as a 'freebie' or in exchange for coupons. The 'freebie' was a highly popular marketing technique towards the end of the 1960s, encouraging consumers to make purchases they otherwise would not have done (Castle and Marriot 1968: 4). The language of 'freebie' paper dress advertisements, and the editorials that promoted them, points to the young target consumer, often described as a 'dolly' or 'dollybird'. Wall's suggested their paper dresses enabled the wearer to be 'cuts above ordinary paper dollies!' (Anon. 1967b: 11). The term 'dollybird' was broadly associated with young, carefree women – interested in the latest fashions and music. The 'dollybird' transcended class – and indeed, much of the fashion of this period was supposedly classless (see Breward 2004: 151–77). Whilst paper dresses were low-cost dresses in reach of most, they were worn by women across the class spectrum who wanted fun, novel clothing.

Young consumers, as the paper dress trend indicates, have always been the key target markets for low-cost fashion. Today, whilst young consumers are increasingly environmentally conscious, they are also amongst the most voracious consumers of fast fashion. A 2021 survey indicated that 64 per cent of British 16–19-year-olds admit to buying clothes they have never worn, compared with 44 per cent of all adults surveyed (Kale 2021: n.pag.). This illustrates that contemporary disposable fashion would need to consider the wants and needs of the young consumers likely to purchase it.

2.3 Experience of wear

In 1966 *Women's Wear Daily* published a series of comments from staffers exploring their experience of wearing a paper dress – largely their views were negative. Complaints related to the drapability of the dresses, seen as 'too stiff' and that the garments were uncomfortable against the skin. Overall, comments highlight that these garments were seen as unflattering, and one writer suggested she felt like 'a frump' (Anon. 1966b: 38–39).

Using an unconventional approach, Liz Tregenza, who is also a vintage dealer, wore a paper dress from her personal collection to better understand how these dresses behaved on the body. The dress used for this experiment is made from a vibrant red paper material which has been reverse-stencilled with a gold logo (Figure 5). The paper material, likely Vilene, is very strong. The reverse of the paper material is visually identical to Dispo garments. The dress is made from six pattern pieces – three main pieces and three internal

Figure 5: Player's cigarette advertising paper dress, c.1967. *© Liz Tregenza*

facing pieces. It has been sewn together, and the two side seams have been overlocked; it also has a zip inserted in the centre back seam. The workmanship is basic, but neat overall. The silhouette means the dress stands away from the body, creating airflow, showing how the dress would be suitable in hot weather. Whilst stood or dancing, the dress behaved as one might expect, moving with the body. However, the paper material does not have flexibility and bags in an unflattering way when seated. Furthermore, the armholes are cut quite large, likely to give flexibility in terms of sizing. As the paper material is very lightweight, this means it does not sit properly, with space above the shoulder. Overall, the biggest issue with the dress is how it feels – when seated this is more obvious; the paper material is itchy and uncomfortable against bare skin.

3. END OF LIFE

In July 1967 a *Guardian* article predicted that by the end of that year sales of 'short-life' dresses were expected to reach $76 million (Anon. 1967c: 8). Despite this prediction, the bottom had dropped out of the market by winter 1967. There were various reasons why paper garments fell from popularity, but one of the biggest issues was price, either deemed too cheap – the cheapest described as 'just about as attractive as paper towels' (Sheppard 1967: 6) – or more often too expensive, to compete with conventional garments (Knight 1969: 4).

Perhaps more enduring than the paper dresses themselves was the fashion cycle they embodied; the same article describes how 'bold prophets' in the trade predicted that within five to ten years there would be a 'great dividing line between quality apparel for long wear and attractive short-wear styles which will be thrown away as casually as a paper napkin' (Anon. 1967c: 8). Certainly, by the mid-1970s the fashion cycle had further sped up; however, paper material was no longer widely used.

Ultimately paper material could not displace the popularity of typical woven and knitted fabrics, nor compete in functionality. Indeed, paper material must be seen against a backdrop of decreasing prices for synthetic fibres. Whilst initially seen as an intriguing possibility, paper was ultimately seen as a gimmick (Knight 1969: 4).

The declining demand for paper clothes from 1968 onwards also reflected a shift in design trends. The properties of paper materials meant they worked best for garments with boxy silhouettes. It was unsuitable for the diaphanous shapes and bias-cut lines, inspired by silhouettes of the 1930s and 1940s, which were becoming fashionable.

3.1 Disposal and survival

Whilst paper dresses were promoted as disposable, they were not recyclable in the modern sense, and many of the materials and processes used in their manufacture were inherently environmentally damaging. The inclusion of nylon, in particular, takes the paper dress from being theoretically compostable to a mixed polymer material. Nylon is manufactured from petroleum, which is non-renewable, non-biodegradable and associated with high emissions of CO_2 (Chen and Burns 2006: 248–61; Boustead 2005: 10; Muthu et al. 2012: 66–74; Muthu 2020). While viscose, also found in some paper dresses, can be made from renewable resources and is biodegradable, it is not necessarily environmentally friendly because of the amount of water, chemicals and effluent used and emitted in its manufacture (Muthu et al. 2012: 66–74). Furthermore, viscose has contributed to the destruction of ancient woodlands and, as a result, has impacted biodiversity (Stenton et al. 2021b: 13). There are also concerns over the use of carbon disulphide, a neurotoxic, volatile component used within viscose production (Philipp 1993: 704–14). Modern processes have worked hard at 'closing the loop' to prevent leakage of hazardous chemicals into the environment (White et al. 2005; Goswami et al. 2009: 455–65), but during the 1960s, the production of viscose was certainly environmentally damaging (Blanc 2016).

In the mid-1960s 'disposability' was a term with positive connotations, synonymous with convenience and saving the consumer time. There was no need to wash paper garments, and their cost was less than laundering similar garments made from cotton or synthetic fibres (Smith 1968: 24). As early

as 1969 however, the problems of disposability were already being discussed; one newspaper article suggested the term 'affluent effluent' was applied to the waste and discarded products of modern society. The article went on to state that 'planned obsolescence [had] brought problems of waste disposal on a scale not previously envisaged' (Anon. 1969: 15). In a domestic setting during the 1960s, there were not the same recycling opportunities that we have today, meaning products were improperly disposed of. The 1969 article cited previously suggested that plastic bottles were 'non-returnable' to store, unlike their glass predecessors, and that many were simply dumped. This is still a problem today, and many consumer goods, despite improved recycling opportunities, are disposed of inappropriately.

4. A PAPER DRESS FOR THE TWENTY-FIRST CENTURY?

The paradigm of disposable dresses as an alternative to current industry practice is not completely novel. Goldsworthy et al. explored this in their Mistra Future Fashion project where they questioned the place of fast garment cycles with appropriate end-of-life mitigations. One outcome of this project was the 'throwaway dress' designed in collaboration with Filippa K – a disposable single-use garment that would 'provide the wearer with an opportunity to update their wardrobe for a special occasion with reduced associated environmental impacts' (Goldsworthy et al. 2019: 45).

In the 1960s, the environmental burden of paper garments was not considered. The chemicals and processes used focused on increasing the functionality of the garments without consideration to the environmental ramifications of their disposal. This is evident in the mixing of paper (theoretically compostable) with synthetic materials such as nylon to improve the handle and drape of the material, the use of petroleum-derived inks in the printing and the coating of garments with environmentally hazardous flame-retardant coating. So, how practically could we create a paper dress for the twenty-first century?

4.1 Manufacture and construction

Paper garments of the 1960s were commonly a combination of 'paper' cellulosic pulp and either nylon or viscose scrim – neither of these added polymers lend themselves to sustainable production or disposal; however, recent efforts have been made in the development of more sustainable, biodegradable polymers (see Patti and Acierno 2022). Lenzing AG, for example, have developed closed-loop processing of viscose for their 'ecovero' and 'lyocell' brands (White et al. 2005: 157–88; Periyasamy and Militky 2020: 63–95). Consequently, today a cellulose-based non-woven material could be developed that was relatively green. Furthermore, a range of new fashion and textile initiatives and organizations are emerging to produce viscose that does not involve harmful deforestation and works to preserve forests and genetic diversity. For example, Canopy works with brands to transform supply chains whilst prioritizing biodiversity and forest protection (Canopy n.d.: n.pag.); Textile Exchange is also supporting regenerative agriculture and has recently published an analysis of the emerging regenerative textile landscape (Textile Exchange 2022); Fashion for Good recently launched the 'Untapped Agricultural Waste Project' with the aim of developing technologies capable of transforming agricultural waste into textile fibres (Fashion for Good 2022); and Fibershed develop regional fibre systems which replenish the soil and protect the biosphere (Fibershed n.d.).

Coloration of 1960s paper dresses used chemistry and processes that have since been proven to have significant environmental costs (Horrocks et al. 2005: 3–12; Kahane 2015: n.pag.). Water-based inks have petroleum-derived plastics present within them, alongside volatile solvents and formaldehyde that pose safety and emission concerns during manufacture (Kahane 2015: n.pag.). Water-based inks also tend to require significant energy to cure due to the need to drive off excess solvent through evaporation (Aydemir and Özsoy 2020: 12). Today, demand for green ink alternatives is growing rapidly. Initiatives such as water-based and UV-curing inks are starting to replace those based on volatile solvents, and petrochemical-derived pigments are being replaced by alternatives sourced from either natural or renewable feedstocks (Robert 2015: 287–92).

Printing technology has advanced since the 1960s, and if paper dresses were made today, digital printing could be utilized. Digital printing reduces the water and ink wasted during the printing process, making it more environmentally friendly and often cheaper and quicker than traditional printing methods (Tkalec et al. 2022: 105–15). The concerns over the flammability of garments made from paper are valid today. While many of the flame-retardant coatings used now remain broadly unchanged since their invention between the 1950s and 1980s (Horrocks et al. 2005: 3–12), there is a push to find sustainable, environmentally benign alternatives (see Horrocks 2020: 2160; Malucelli 2020: 4046; Piao et al. 2022: 2711–29; Zhu et al. 2022: 106–688).

Garment construction would also need to be carefully considered. In order to make an affordable and environmentally friendly garment, it would need to be simply manufactured – either with as few stitched seams as possible or with bonded seams. This should guarantee more straightforward disposal, but also simple manufacturing would help ensure that those making the garments could be paid fair wages for their work.

4.2 Consumer experience

Paper dresses were targeted at the youth market in the 1960s. Today, it is that same market that heavily consumes fast fashion, and consequently they would be the ideal target market for a contemporary paper dress. In Britain, Pretty Little Thing (PLT) – part of the Boohoo Group – is amongst the most popular fast fashion brands with the 16–24 demographic. PLT offers their garments at extremely low prices; party dresses typically cost £30 or less, and regular discounts are offered. The company came under criticism for their '100% off' sale in November 2021, effectively offering garments for free (Rogers 2021: n.pag.).

Extremely low-cost fashion encourages excessive consumption and decreases clothing utilization – the average number of times a garment was worn before it ceased to be used decreased by 36 per cent between 2002 and 2017. Consequently, many garments are estimated to be discarded after just seven to ten wears, and as a 2017 report by the Ellen MacArthur Foundation indicated, more than half of fast fashion produced is disposed of in under a year (2017: 19, 36).

The speed at which fashion is consumed is intimately connected with social media; there is a continuous thirst for new outfits to post on Instagram or TikTok. PLT heavily target consumers through social media, working closely with influencers and reality TV personalities of a similar age to their consumer,

such as Gemma Owen, appointed a brand ambassador in 2022 at just 19, and Molly-Mae Hague, appointed creative director of PLT in 2021.

It is inevitable that some consumers will wear garments simply for social media content creation or a night out. Rather than deny this, a change in mindset around material choice and matching speed cycles for such garments could offer an innovative solution.

4.3 End of life

In order to create an environmentally friendly paper dress, more sustainable coloration and coating chemistry could be utilized with compostability in mind. The nylon present in some paper garments could either be replaced by a compostable fibre, or the paper itself chemically modified to improve drape and strength. Progress is being made in the development of materials created from agricultural waste, which could enable the creation of garments that are compostable or biodegradable. Designers such as Suzanne Lee have experimented with fully compostable materials made from waste, and in Italy, 'Orange Fiber' is currently working with citrus waste to produce textiles (Biofabricate n.d.; Orange Fiber n.d.). Finally, household recycling and composting infrastructure more broadly would also need to be improved to make an environmentally friendly disposable dress truly viable.

CONCLUSION

Undoubtably, there is a lot of work still to be done to transform the historical design of the paper dress into a commercially viable and consumer-attractive product, but the concept of a truly compostable, 'disposable' garment to help alleviate the environmental burdens represented by the current ultra-fast fashion cycle should not be disregarded.

The 1960s paper dress trend was extremely short-lived, but briefly provided consumers with viable garments designed for single (or limited) use. Whilst the paper dresses themselves were not sustainable, this technology, as we have shown, could be reimagined today. This paper has utilized cross-discipline collaboration, bringing together designers, historians, chemists and textile engineers to explore the history and potential future of the paper dress.

Presently the discourses around sustainable systems for fashion have centred around rejection of the fast fashion cycle in favour of slower methods of consumption. This argument assumes that fast fashion is inherently negative, yet its prominence persists. While some consider fast fashion to be a new phenomenon, originating in the twenty-first century, it is clear that the desire for rapid modes of fashion consumption were present during the twentieth century.

In 1967, Glen Seaborg predicted the year 2000 would bring low-cost disposable dresses made from new synthetic fabrics, enabling women to never be seen in the same outfit more than once (Anon. 1967b: 15). At the time, the idea of using synthetics for disposable fashion was exciting; however, now the ramifications of these materials are better understood; it is rightfully unsettling.

The current trend of ultra-fast fashion cycles is essentially creating pseudo-disposable clothing, with prices set so that a garment is financially comfortable to purchase with a single wear in mind. However, the materials and processes used are designed for extremely long-lived products, with synthetics that take hundreds of years to degrade and pose significant environmental challenges while doing so. It is the authors' belief that through continued similar collaborative efforts, the sustainable future of the textile industry can be based on concepts from the past combined with modern knowledge and techniques to design and build a more sustainable future.

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10.6.5 Paper 5: A Dye-fibre System From Food Waste: Dyeing Casein Fibres With Anthocyanins

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Coloration Technology

ORIGINAL ARTICLE

A dye–fibre system from food waste: Dyeing casein fibres with anthocyanins

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Abstract

Regenerated protein fibres manufactured from food side-streams offer significant potential as circular and sustainable fibres, but greater knowledge of their dyeing properties is required. In this research, coloration of casein fibres with dyes also extracted from blackcurrant skins left over from juice pressing is explored. Casein fibre was dyed with blackcurrant extract, rich in anthocyanins, from pH 2 to pH 6 and from 40 to 80°C, with and without alum. Casein fibres could be dyed with blackcurrant extract across all conditions tested, and under optimal conditions, dyeing is achieved with medium depths of colour with good wash fastness. Highest sorption of anthocyanins onto casein is observed at pH 4, where anthocyanins are a mixture of 60% neutral purple quinonoidal base form and 40% flavylium cation form; under these conditions dye–fibre interaction is optimal. At pH 2, casein fibre has a highly positively charged surface and anthocyanin is in the flavylium cation form, leading to some dye–fibre repulsion. At pH 6, the slightly negatively charged casein fibre demonstrates lower sorption of the mixture of 40% purple quinonoidal base form and 60% the anionic quinonoidal base form, again leading to some dye–fibre repulsion. Presence of alum in the dyebath enhances sorption of anthocyanins onto fibre at pH 4 due to formation of Al–anthocyanin complexes. Wash fastness of the dyeings is better as pH increases and as temperature increases.

1 | INTRODUCTION

Global annual fibre production in 2021 was over 113 million tonnes (Mt) and is expected to grow to 149 Mt by 2030,[1] with polyester (60.5 Mt) and cotton (24.7 Mt) making up 76% of the total; regenerated cellulosics (e.g., lyocell, viscose; 7.2 Mt), other plant fibres (e.g., linen, hemp; 6.7 Mt), polyamides (5.9 Mt), other synthetics including polypropylene, acrylics, and elastane (5.8 Mt), wool (1.0 Mt), and other animal fibres (0.7 Mt) make up the remainder. Apparel consumption set to rise to 102 Mt by 2030 (a 63% increase from today),[2] and with this increased fibre use comes increased consumption of raw materials, water, energy and chemicals used in their manufacture, and the associated emissions to the environment.

Fibres derived from petrochemical resources receive much media attention for their contribution to the global problem of 'plastics' in the environment. Synthetic microfibres (MFs) account for over a third of all plastic reaching the open ocean[3] and are pervasive in all ecosystems, but natural fibres also have a significant impact; recent studies show ~80% of ocean MFs are dyed/finished cellulosic fibres,[4] the impact of which are not yet understood. Wool remains the dominant protein-based fibre for textiles, but recycled wool only contributes 6% of the global total wool market.[1]

There is a clear need to move away from the traditional sources of textile fibres to find options that present more material circularity. In a circular economy, waste and pollution can be reduced and eliminated by increased use of renewable energy, reducing water consumption, ending the use of toxic chemicals, and the design of new materials, products and systems.[5] Utilisation of waste as raw material feedstock is a core concept of circular design. The textile industry has seen in recent years new fibres come into the market that comprise waste as part of the raw materials in their manufacture,[6] such as *Refibra*[7] from pre- and post-consumer cotton waste, *Orange Fibre*[8] from orange peel waste and *Piñayarn*[9] from pineapple leaves. The use of food production waste offers a huge opportunity with benefits to the environment and economy. Up to 2 billion (bn) tonnes per annum (tpa) of all food produced in the world ends up as waste, a carbon footprint of 3.3 bn tonnes carbon dioxide equivalent (CO_2e), which represents about 8% of global greenhouse gas (GHG) emissions.[10,11] Not all food waste is avoidable, and unavoidable by-products from food manufacturing offer an exploitation opportunity for fibres.

But the use of food by-products for making fibres is not a new concept. Regenerated protein fibres (RPFs) have been around for over 100 years, and most of these were manufactured from food side-streams from processing of peanuts, soy, milk and other protein-rich by-products.[6,12] Although these fibres were commercialised as azlons, RPFs were superseded with the advent of synthetic fibres, most notably nylon, due the higher tensile properties, and lower cost.

However, the significant potential for circularity and sustainability of these fibres has reignited interest in their contemporaneous use. One notable example is RPF made from casein extracted from milk waste. According to WRAP (Waste & Resources Action Programme),[13] the UK dairy industry produces ~555,000 tpa of waste from production, which is either incinerated or spread on land; the chief by-product of cheese-making is whey (~228,000 tpa), which contains a significant amount of casein. Furthermore, 82% of milk protein is casein with the remainder being comprised of whey; whey is already utilised in the dietary supplement industry, but the uses for casein are fewer, hence casein from food waste presents an attractive opportunity for valorisation. Recently, the German company QMILK has produced a RPF from casein, which the company claims to be zero-waste and free of hazardous chemicals.[14]

If RPFs are to have a renaissance as textile fibres, then their coloration is of keen interest. There is limited published literature on the sorption of dyes on casein fibre, but it has been demonstrated that the dyeing behaviour of non-metallised and metal complex acid dyes onto the fibre follows similar trends to acid dyes on wool.[15,16]

However, is the use of synthetic acid dyes on casein commensurate with the circularity of the fibre? Alternatively, circularity for RPFs could be partnered with circularity of the colourants applied to dye the fibres. Rose et al[17] demonstrated that anthocyanins extracted from blackcurrant fruit waste gave intense blue-coloured dyeings on human hair. There are many sources of anthocyanins from fruit waste from both the juice pressing and wine manufacturing industries, so this is a potentially untapped raw material for the production of sustainable dyes.

Anthocyanins are the largest group of polyphenolic pigments in the plant kingdom; they are non-toxic, water-soluble, and responsible for pink, red, purple, violet, and blue coloration in fruits, vegetables, and flowers. Their colours are determined by small differences in the chemistry of the different anthocyanins. Anthocyanins take part in acid–base equilibria in aqueous solutions, and a general scheme of reactions (Figure 1) highlights the important equilibrium forms: in aqueous solution at pH < 3, the anthocyanin is red, and the flavan nucleus exists mainly as the very stable flavylium cation (**AH**$^+$). Increasing pH leads to kinetic and thermodynamic competition between two reactions. When pH increases, **AH**$^+$ undergoes a rapid deprotonation reaction (pK_{a1} ~ 3.7) to form the purple quinonoidal base (**A**) as the kinetic product, which leads to formation of the anionic quinonoidal base (**A**$^-$) at higher pH (pK_{a2} ~ 7) that has a blue colour.[18–21] The alternative thermodynamically favoured colourless hemiketal (**B**) is relatively slowly formed via hydration above pH 2, at position 2 (pK_h 2–3). Ring opening is also slow compared to deprotonation, but typically faster than hydration and can lead to the formation of the yellow *E*-chalcone (**C**$_E$), although for many common anthocyanins this is a relatively minor component of the equilibrium. Once formed, **C**$_E$ isomerises to give the *Z*-chalcone (**C**$_Z$).[22]

Herein, the intention of this research was to use anthocyanins extracted from waste blackcurrant material in the dyeing of casein fibres to produce a potentially sustainable and circular dyeing system. In addition, the optimal dyeing conditions in terms of colour strength and wash fastness was to be determined, and to ascertain if the colour change in anthocyanins observed at different pH values could be used advantageously to produce a range of shades from one dye material. We also include the utilisation of alum as a *meta*-mordant to determine if its inclusion in the dyeing process has any influence on dye sorption, resultant dyeing shade, and subsequent fastness properties; aluminium is a well-known mordant

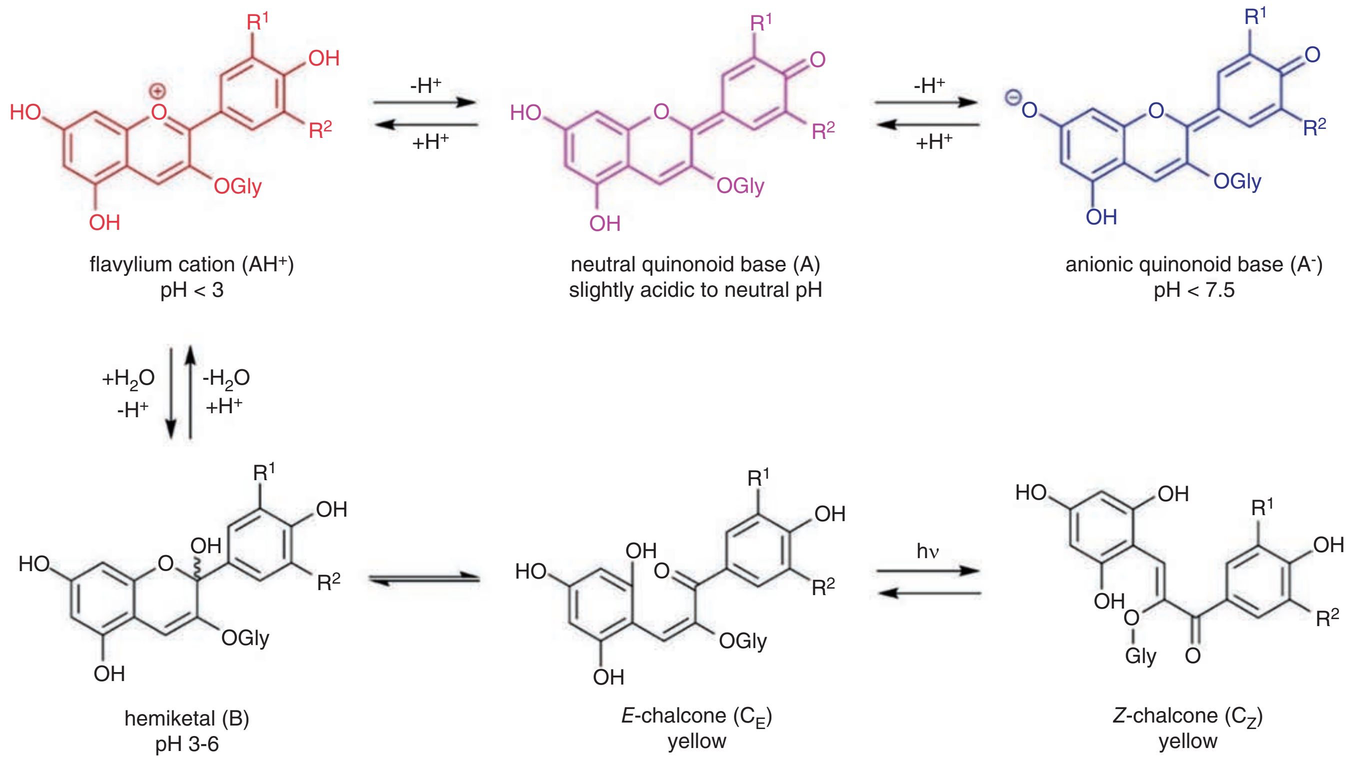


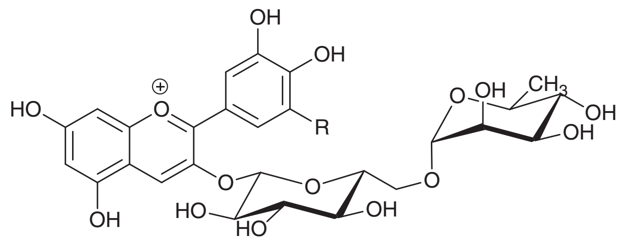
FIGURE 1 Effect of pH on anthocyanin structure and resultant colour.

for natural dyes on natural fibres, but also forms particular structural complexes with anthocyanins that influences colour, as will be discussed later.

2 | MATERIALS AND METHODS

2.1 | Materials

"Milk Protein" (casein) fibre sliver was obtained from George Weil, Guildford, UK. Blackcurrant (*Ribes nigrum* L.) pomace was obtained from A&R House, UK; the raw fruit grown in the UK had been pressed in production of blackcurrant cordial (*Ribena*). The crude waste is referred to as pomace, which comprises the fruit epicarp (*c.* 50 wt %), seeds (*c.* 45 wt%) and extraneous matter (e.g., berry stalks, *c.* 5 wt%). Seeds are separated from this pomace and unwanted stalks removed; the subsequent material received was predominantly dried blackcurrant fruit epicarp. Dried blackcurrant extract dye powder was extracted from the dried blackcurrant fruit epicarp using the method described in Farooque et al[23]; the main dye components in the blackcurrant powder are anthocyanin glycosides, which are present as delphinidin-3-*O*-rutinoside (Dp3rut; **1**; 22.6%), cyanidin-3-*O*-rutinoside (Cy3rut; **2**; 20.4%), delphinidin-3-*O*-glucoside (Dp3glc; **3**; 7.7%), and cyanidin-3-*O*-glucoside (Cy3glc; **4**; 4%), the remaining components are a mixture of polymeric anthocyanins (18%), flavonoids (17%), and hydroxycinnamates (9%). Woolly Wash detergent (anionic surfactants, amphoteric surfactants, lanolin, fragrance and preservative) was obtained from Mitchell's Wool Fat Soap, Bradford, UK. Multifibre DW fabric was obtained from SDC. General purpose chemicals were obtained from Sigma-Aldrich, UK.



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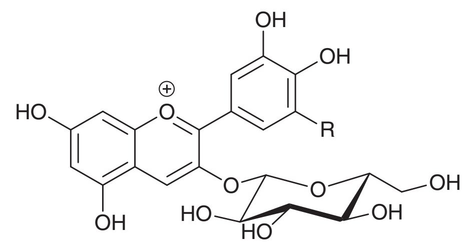
2: R = H



3: R = OH
4: R = H

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2.2 | Dyeing process

Casein fibres were dyed in an aqueous solution with 5% owf blackcurrant dye powder, with optional inclusion 1% owf of potassium aluminium sulfate dodecahydrate (alum). Based on the ratio of the anthocyanin glycosides present in the blackcurrant powder, each gram of blackcurrant powder contained 0.55 g anthocyanin, with an average molecular weight of 595 g mol^{-1}, equivalent to 0.92×10^{-3} mol. For every gram of blackcurrant powder, 0.2 g alum was added, equivalent to 0.42×10^{-3} mol of aluminium ion (Al^{3+}). This is approximately equal to a 2:1 ratio of anthocyanin glycoside to Al^{3+} and was intentionally applied to encourage formation of such 2:1 complexes in the fibre.

Dyeing was conducted at varying pH values (pH 2, 4, and 6) using formic acid and sodium hydroxide to modify pH, in an Ugolini Redkrome II dyeing machine, using a liquor–fibre ratio of 20:1. Fibres were introduced to the dyebath at room temperature and temperature increased at the rate of 1°C min^{-1} until the dyeing temperature ($T = 40$, 60, 80 and 98°C) was achieved, and samples held at the dyeing temperature for 30 min. After dyeing, fibre and fabric samples were rinsed in cold water and dried in ambient conditions prior to colour measurement.

2.3 | Wash fastness testing

Samples were subjected to a modified wash fastness test based on ISO 105-C06:2010 protocols using SDC Multifibre DW fabric as adjacent. Briefly, 1 g samples of dyed fibre were washed in individual pots in a James Heal GyroWash Colour Fastness Tester. Pots were filled with 50 cm^3 of an aqueous solution containing 1 g dm^{-3} of Woolly Wash detergent and the fibre/fabric sample and multifibre fabric adjacent added. Samples were washed for 30 min at 30°C. After washing the samples were rinsed, dried, and colour change ascertained from colour measurement before and after washing. The washed samples were also visually assessed using grey scales according to the ISO 105-A03:2019 test protocol to determine the degree of staining. The grey scale ranges from 5 for no stain on the adjacent fibres down to 1 for a severe staining, with half points in between.

2.4 | Colour measurement

Dyed fibre and fabric samples were measured using a Datacolor 500 colour spectrophotometer connected to a personal computer using Datacolor software. From reflectance (R) values at a specified wavelength (λ) of the dyeings, the colour strength (K/S) of the sample was calculated using the Kubelka–Munk equation (Equation 1).

$$\frac{K}{S} = \frac{(1-R)^2}{2R} \tag{1}$$

Tone of the colour of the dyeings was quantified in terms of L^*, a^* and b^* values within the CIELab system. Colour difference (ΔE) between samples before (L^*_1, a^*_1, b^*_1) and after (L^*_2, a^*_2, b^*_2) washing was quantified by Equation (2):

$$\Delta E = \sqrt{\left(L_2^* - L_1^*\right)^2 + \left(a_2^* - a_1^*\right)^2 + \left(b_2^* - b_1^*\right)^2} \tag{2}$$

The human eye can perceive difference in colour when the ΔE value between two samples is greater than 2 units. Change in lightness values (ΔL) between samples before (L^*_1) and after (L^*_2) washing was quantified by Equation (3):

$$\Delta L = L_2^* - L_1^* \tag{3}$$

3 | RESULTS AND DISCUSSION

Quantitative work was carried out with dyeings using anthocyanin-rich blackcurrant extract across different pH and temperature, with and without alum. From the dyeing results (Figure 2), it is observed that greater colour strength is achieved as temperature increases, which is to be expected as the higher energy affords greater solubility of the dye, greater fibre swelling, and lower viscosity of water, in alignment with general theory of dyeing, which will promote greater sorption and diffusion of the dye within the fibre substrate. In the limited research into dyeing casein fibres, there is evidence that the sorption of non-metallised and metal complex acid dyes onto the fibre follows similar trends to acid dyes on wool, insofar as sorption of acid dyes increases with decreasing pH from pH 7 to pH 2, with a significant increase in sorption from pH 4 to pH 2 in particular.[16] Skinner and Vickerstaff concluded that sorption isotherms of three non-metallised acid dyes on wool and casein fibre at pH < 2 were almost identical.[15] Sorption of anthocyanins onto casein fibre do not follow these trends for acid dyes on casein; highest sorption of anthocyanins is observed at pH 4, which is even higher in the presence of alum.

Protein fibres are amphoteric, meaning that under different conditions they can adsorb acids and bases with equal efficiency. The charge a protein carries at a given pH is relative to the number of side chains that

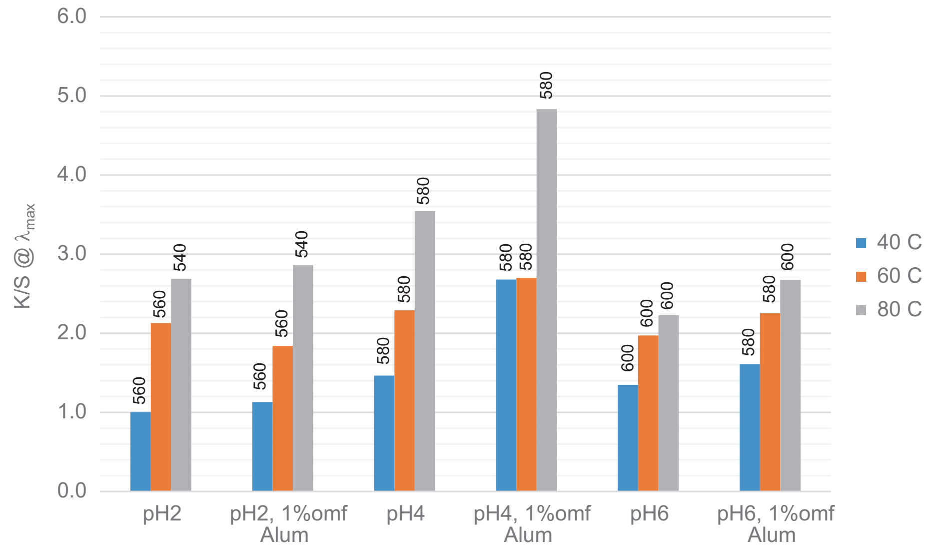

FIGURE 2 Colour strength (K/S) at maximum wavelength (λ_{max}) of dyeings of casein fibre with blackcurrant extract powder with varying, pH, temperature and inclusion of alum. Number on top of column indicates observed λ_{max} of dyeing.

contain $-NH_2$ and $-COOH$ and the pK_a values of those side chains. This can be illustrated using the model of a theoretical water-soluble protein, as described by Sumner,[24] in which the protein contains 100 aspartic acid residues (pK_a of $-COOH$ groups = 3.86), 30 lysine residues (pK_a of $-NH_2$ groups = 8.95) and 50 arginine residues (pK_a of $-NH_2$ groups = 13.2). Using this model, the net charge of the protein is +79 at pH 2, +22 at pH 4, and −18 at pH 6. In casein protein, positively charged side chains are arginine (209 μmol g^{-1}), histidine (179 μmol g^{-1}), and lysine (592 μmol g^{-1}); negatively charged side chains are aspartic acid (606 μmol g^{-1}) and glutamic acid (1651 μmol g^{-1}).[25] By comparison, in virgin merino wool, positively charged side chains are arginine (600 μmol g^{-1}), histidine (82 μmol g^{-1}), and lysine (269 μmol g^{-1}); negatively charged side chains are aspartic acid (560 μmol g^{-1}) and glutamic acid (1049 μmol g^{-1}).[26] As the isoelectric point of casein protein is pH 4.6,[27] this is very close to the Sumner model, so when dyeing at pH 4, where greatest anthocyanin sorption was observed, the casein fibre will have a slightly positive ζ-potential.

The form of the anthocyanin is also critical to dye sorption onto any charged substrate. Work by Nave et al.[28] on the closely related anthocyanin malvidin-3-glucoside (Mv-3-glc) demonstrated that the mole fractions of flavylium cation (**AH**$^+$) form, quinonoidal base (**A**) form and anionic quinonoidal base (**A**$^-$) form vary with pH (Figure 3). It would be expected that at pH 4 the anthocyanins present would be a mixture of *c*. 60% neutral purple quinonoidal base (**A**) form with and 40% flavylium cation (**AH**$^+$) form (Table 1); under these conditions dye–fibre interaction between anthocyanins and casein protein is optimal, as observed through highest dye uptake.

As the overwhelming majority of dyes applied to protein fibres (mainly wool) are anionic, there is little knowledge around the sorption of neutral species onto the substrate. The exception is 1:1 metal complex acid dyes, many of which have an overall net neutral charge. Lemin and Rattee[29] observed when applying C.I. Acid Orange 74 and C.I. Acid Orange 76 (neutral 1:1 chromium complexes) to wool, exhaustion increases significantly as dyebath pH decreased from pH 7 to a maximum around pH 4, which is maintained with further pH reduction to pH 3; however, reduction of dyebath pH to pH 2 caused a decrease in exhaustion. They remarked that the “decrease in exhaustion from the maximum value on further lowering of the dyebath pH is a phenomenon not observed with any other range of dyes used in wool dyeing.” Burkinshaw states that the nature of interactions between 1:1 metal complex dyes and wool remains a matter of debate,[30] and no author offers a satisfactory explanation for why sorption of neutral 1:1 metal complex acid dyes is observed to be optimal at pH 4.

It may be that at pH 4 when the ζ-potential of casein is only slightly positive that other non-electrostatic sorption interactions of neutral dyes with the substrate, such as hydrophobic interactions and hydrogen-bonding interactions, are more important to sorption than at other pH values where electrostatic interactions dominate. Hence, at pH 4 where the neutral quinonoidal base (**A**) form of anthocyanins is highest, greatest sorption onto a similarly neutral/slightly positive surface is observed. It is noted that the **A** form of Mv-3-glc is highest at around pH 4.8,[28] which is also close to the casein isoelectric point (pH 4.6). Although the anthocyanins found in blackcurrant are slightly different to Mv-3-glc, it may that with further research an even more optimal pH for sorption of

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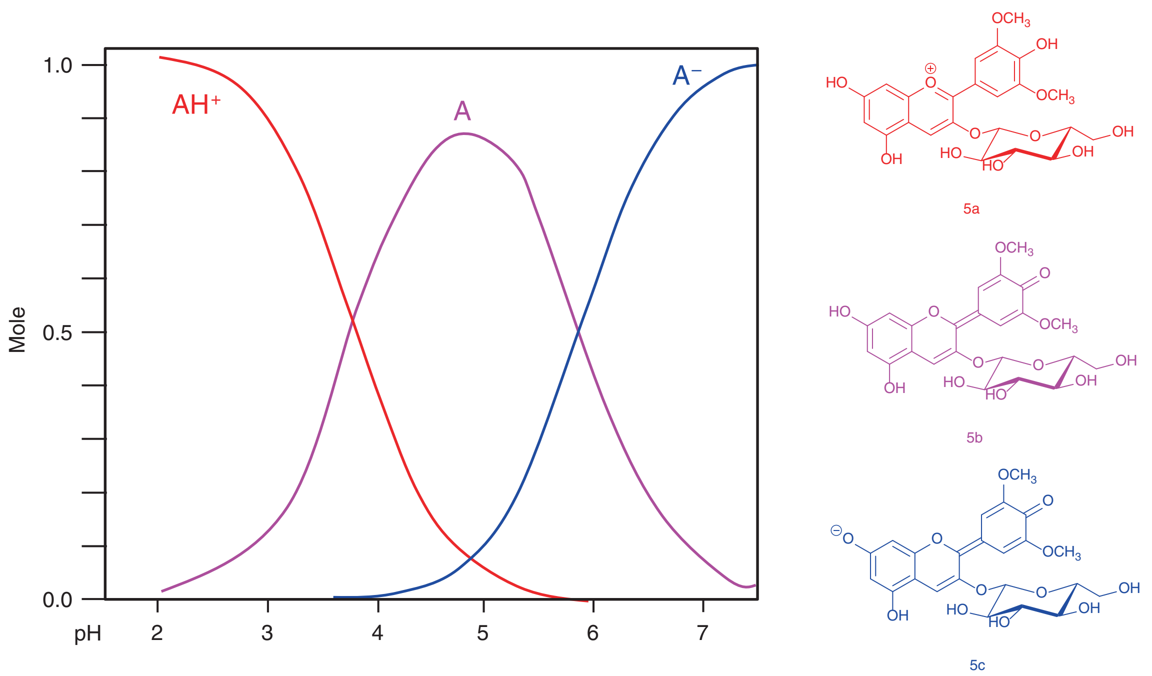

FIGURE 3 Mole fractions of malvidin-3-glucoside (Mv-3-glc) **AH**$^+$ (**5a**), **A** (**5b**) and **A**$^-$ (**5c**) forms with varying pH using data from Nave et al.[28]

TABLE 1 Summary of charge of model protein and form of anthocyanin with varying pH values.

pH	Charge on model protein	Mole fraction of anthocyanin AH$^+$	A	A$^-$
2	+79	1.00	0.00	0.00
4	+22	0.39	0.61	0.00
6	−18	0.00	0.42	0.58

blackcurrant anthocyanins onto casein may be found closer to pH 4.8.

Figure 2 also shows the observed maximum wavelength (λ_{max}) of the dyeings obtained at different pH values. At pH 2, anthocyanins in blackcurrant have λ_{max} of approximately 520 nm, then along the deprotonation sequence, λ_{max} typically shifts by 20–30 nm to 540–550 nm (**AH**$^+ \rightarrow$ **A**), then by 50–60 nm to around 600 nm (**A** $\rightarrow$ **A**$^-$).[28] However, the observed λ_{max} of the dyeings achieved at pH 4 was 580 nm; if at this pH the primary species adsorbed is the neutral purple quinonoidal base (**A**) form with λ_{max} of 550 nm, why was the colour on substrate observed at a λ_{max} 30 nm higher?

When dyeing human hair with the same anthocyanin extract at pH 5, Rose et al[17] also observed λ_{max} at 580 nm; they attributed this to sorption of the purple quinonoidal base (**A**) form of the dye, but that the hair provided an environment that enabled the anthocyanins to convert to **A**$^-$ on adsorption, being stabilised by electrostatic interaction with protonated primary amino functions ($-NH_3^+$) in arginine (499 µmol g^{-1}), histidine (64 µmol g^{-1}), and lysine (218 µmol g^{-1}) residues all present in human hair.[31] It may be that the same stabilisation effects were observed herein for casein, despite the levels of those three positively charged side chains being slightly different.

Observations of sorption effects at pH 4 can be compared with dyeings at pH 2, where the casein fibre would have an even higher positive ζ-potential and the anthocyanin would be around 100% the flavylium cation (**AH**$^+$) form, which may lead to some dye–fibre repulsion, limiting uptake. It is clear that sorption of dye still occurs, and it is noted that λ_{max} of the dyeings at pH 2 was 540–560 nm, which would be expected from sorption of a mixture of the flavylium cation (**AH**$^+$) form and the quinonoidal base (**A**) form of the anthocyanins, which have λ_{max} of *c.* 520 nm and 550 nm, respectively.

At pH 6, the casein fibre would have a negative ζ-potential and the anthocyanin would be a mixture of *c.* 40% the purple quinonoidal base (**A**) form and 60% the anionic quinonoidal base (**A**$^-$) form, which again may lead to some dye–fibre repulsion, limiting uptake. Sorption of dye still occurs, and it is noted that λ_{max} of the dyeings at pH 6 was 580–600 nm, which would be expected from sorption of a mixture of a minority of neutral quinonoidal base (**A**) form and majority of anionic quinonoidal base (**A**$^-$) form the anthocyanins, which have λ_{max} of *c.* 550 nm and 600 nm, respectively.

Whilst the addition of a *meta* mordant of alum did not make a significant difference to sorption of the dye at pH 2 and pH 6, the presence of alum in the dyebath enhanced the sorption of the anthocyanin onto the fibre at pH 4. Understanding this observation is aided by research into Al–anthocyanin complexes in nature. Petals of *Hydrangea macrophylla* (Thunb.) Ser. change from red through purple to blue, depending on cultivation conditions; in acidic soils (pH < 5.0), the level of water-soluble Al^{3+} in soil is increased and absorbed by the roots, and Al^{3+} forms complexes with anthocyanins resulting in blue petal colour. This colour originates from one single anthocyanin, Dp3glc (**3**) in a 1:1:1 ratio with Al^{3+} and a co-pigment, either 5-*O*-caffeoylquinic acid (**6**) or 5-*O*-*p*-coumaroylquinic acid (**7**). The identified complex was named "hydrangea blue-complex" (Figure 4).[32,33] Other researchers working with Al–anthocyanin complexes have found that in very acidic aqueous conditions the flavylium cation (**AH**$^+$) dominates and no complexation with Al^{3+} takes place. As pH increases, a new species is formed, with a different colour from the quinonoidal base (**A**), and consistent with formation of an Al–anthocyanin complex, which is stable from 3 < pH < 6. In the pH range 6 to 8.5, the anionic quinonoidal base (**A**$^-$) forms, but at this pH the aluminium salt is insoluble and precipitation occurs. For more basic pH values the system is not stable.[34]

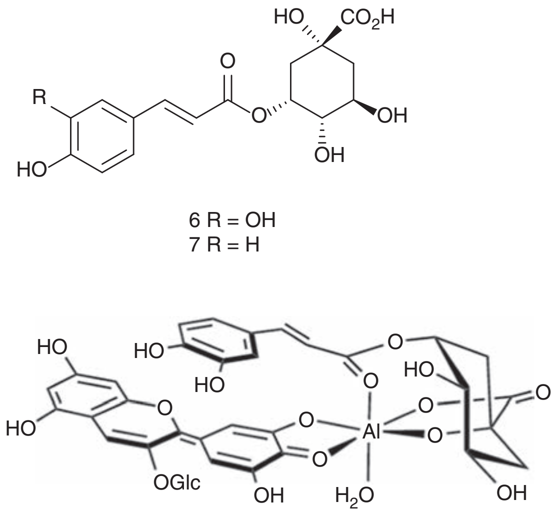

FIGURE 4 Proposed structure of hydrangea blue-complex.

Hence, it is understandable for dyeings herein, where a combination of anthocyanins and alum were applied simultaneously onto casein fibre, that the dyeings at pH 4 with alum are most likely to form Al–anthocyanin complexes, and less likely to form when the same combination was applied at pH 2 and pH 6. Formation of a blue complex with aluminium observed herein is made more likely by the application of a blackcurrant extract that contained other polyphenols in addition to anthocyanins, most notably caffeic acid (3%) and *p*-coumaric acid (5%),[23] which could assist with blue complex formation, as observed for the hydrangea blue-complex. The observed increase in colour strength of the dyeings at pH 4 with alum could be as a result of the ability of the formed Al–anthocyanin complex to have more extensive hydrophobic interactions with the casein substrate due to the overall size of the complex, compared to the single anthocyanins, hence promoting greater dye uptake.

Observations on the wash fastness of the casein dyeings with anthocyanins are summarised in Table 2 for shade change (Δ*E*) and change in lightness value (Δ*L*) during washing, and Table 3 for staining to cotton (in general only staining of the cotton component of the adjacent Multifibre DW fabric was observed). It can be seen from Table 2 that wash fastness is better as pH increases and as temperature increases. Overall dyeings at pH 4 and pH 6 at 60 and 80°C all provide very good wash fastness performance. No significant difference in wash fastness performance was observed when alum was used. The higher Δ*E* values for dyeings at pH 2 are not due to colour loss, as evidenced by the very small Δ*L* values, but primarily associated with colour change from a purple colour to a blue colour. As shown in Figure 5 for dyeings at pH 2 at 40°C, dyeings before washing have λ_{max} of *c.* 550 nm (associated with the quinonoidal base (**A**) form of the anthocyanins) and dyeings after washing have a λ_{max} of *c.* 580 nm, which is

TABLE 2 Colour change values for casein fibre dyed with blackcurrant extract powder (with varying, pH, temperature and inclusion of alum) following wash fastness testing.

	40°C				60°C				80°C			
	No alum		1% owf alum		No alum		1% owf alum		No alum		1% owf alum	
pH	Δ*E*	Δ*L**	Δ*E*	Δ*L**	Δ*E*	Δ*L**	Δ*E*	Δ*L**	Δ*E*	Δ*L**	Δ*E*	Δ*L**
2	7.9	1.8	8.5	3.6	6.8	1.0	7.5	0.7	6.9	1.2	8.4	−1.7
4	9.5	7.1	6.4	3.8	3.1	0.9	3.4	0.3	4.2	3.4	7.9	7.2
6	4.9	1.5	5.3	3.1	2.1	2.0	5.5	1.2	2.0	1.2	2.0	1.6

TABLE 3 Grey scale staining ratings for transfer to cotton portion of Multifibre DW fabric from casein fibre dyed with blackcurrant extract powder (with varying, pH, temperature and inclusion of alum) following wash fastness testing.

	40°C		60°C		80°C	
pH	**No alum**	**1% owf alum**	**No alum**	**1% owf alum**	**No alum**	**1% owf alum**
2	4/5	4/5	4/5	4/5	4/5	4/5
4	3/4	3	4/5	4	5	4/5
6	4/5	3	4/5	5	5	4/5

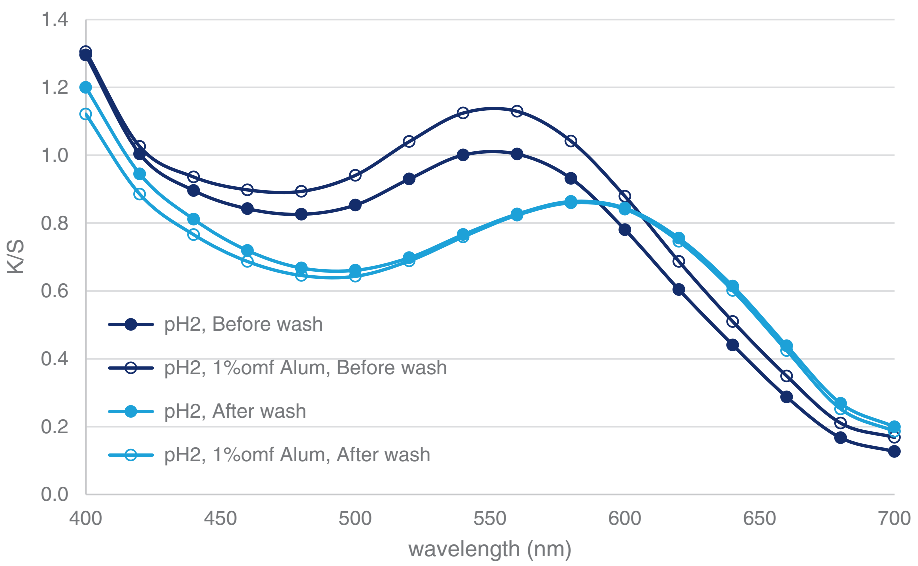

FIGURE 5 Colour strength (*K*/*S*) spectra of casein fibres dyed with 5% owf blackcurrant extract at pH 2 at 40°C, with and without alum, before and after wash fastness testing.

most probably a result of a significant proportion of the adsorbed anthocyanins changing in situ to the anionic quinonoidal base (**A**$^-$) form the anthocyanins (λ_{max} *c.* 600 nm). Change in λ_{max} of the dyeings at pH 4 and pH 6 was less significant. The pH of the wash fastness test solution was pH 7, so it is clear from these results that the dyeings at pH 2 were unstable to washing in this environment at a higher pH than their application pH value, causing hue change. However, dyeings at pH 4 are more stable to changes in hue on washing, despite the washing pH still being higher than those of their application conditions; it is possible that the stronger association between dye and fibre at this pH, as discussed earlier, could stabilise the dye in situ and provide some protective effect to change in the form of the adsorbed anthocyanin.

From grey scale staining ratings for transfer of dye to the cotton portion of the Multifibre DW fabric following wash fastness testing, it can be seen that, in general there was minimal staining of the fibre at higher application temperatures. Some staining of the cotton fibre was noted for dyeings at 40°C, and it is suspected that the lower application temperature is associated with lower diffusion of the dye within the fibre structure, hence, the dye is easier to remove from the periphery of the fibre. This is typical of many dye–fibre systems and is unsurprising.

4 | CONCLUSIONS

Casein fibre dyeing using sustainably sourced anthocyanin colourants from food by-products is demonstrated. By optimising dyeing conditions, dyeing is achieved with medium depths of colour with good wash fastness. Highest sorption of anthocyanins is observed at pH 4. At pH 4, anthocyanins in the colourant extract are a mixture of 60% neutral purple quinonoidal base (**A**) form and 40% flavylium cation (**AH**$^+$) form, and under these conditions dye–fibre interaction between anthocyanins and casein protein is optimal, due to sorption of the neutral form of the dye onto a slightly positively charged surface. At pH 2, casein fibre has a highly positively charged surface and anthocyanin is in the flavylium cation (**AH**$^+$) form, leading to some dye–fibre repulsion, limiting uptake. At pH 6, the slightly negatively charged casein fibre demonstrates lower sorption of the mixture of 40% purple quinonoidal base (**A**) form and 60% the anionic quinonoidal base (**A**$^-$) form, again leading to some dye–fibre repulsion, limiting uptake.

Presence of alum in the dyebath in an approximate 2:1 ratio of Al–anthocyanin enhances sorption of anthocyanins onto fibre at pH 4; these conditions provide the most likely environment to form Al–anthocyanin complexes, leading to more extensive hydrophobic interactions with the casein substrate, promoting greater dye uptake.

Wash fastness of the dyeings is better as pH increases and as temperature increases. Overall, dyeings at pH 4 and pH 6 at 60°C and 80°C all provide good wash fastness performance. No significant difference in wash fastness performance was observed when alum was used. In general, minimal staining of adjacent fibres was observed at higher application temperatures.

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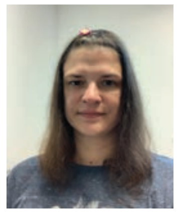
Marie Stenton is a BFTT researcher and PhD candidate at London College of Fashion, University of the Arts London, and a New Scholars Research Fellow with the AHRC Bath and Bristol Creative R+D programme. Her current research focuses on regenerated protein fibres created from food waste alongside the development of a transdisciplinary design methodology.



Alenka Tidder is Coloration Scientist at Keracol Limited. She holds a Masters degree in Textile Technology from the University of Ljubljana, and a PhD from the University of Leeds, where her research focused on the coloration of genetically modified cotton to reduce the environmental impact of the dyeing process. Her areas of expertise include textile coloration, dyeing, hair dyes, natural products and cosmetics.

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10.6.6 Paper 6: Colouration In Flow: The Potential Impact Of In Situ Colouration Of Casein Fibres To Mitigate Environmental Impact Of Transitional Dyeing Mthods

Coloration in Flow: The Potential of In Situ Coloration of Casein Fibers to Mitigate Environmental Impact of Traditional Dyeing Methods

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Letter

Coloration in Flow: The Potential of *In Situ* Coloration of Casein Fibers to Mitigate Environmental Impact of Traditional Dyeing Methods

Joseph A. Houghton,* Alenka Tidder, Marie Stenton, and Richard S. Blackburn

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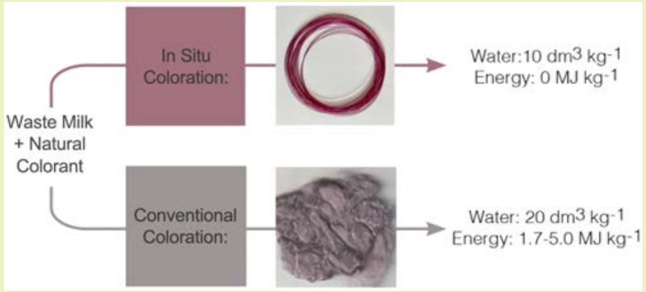
ABSTRACT: The environmental impact of the textiles and food industries can no longer be ignored, and while combining natural protein-based fibers with natural colorants, each derived from food waste, has the potential to offer increased sustainability based on a circular economy, it fails to address other environmentally detrimental textile production steps, such as coloration. This work explores the potential of a new, novel method for *in situ* coloration of regenerated protein fibers using an anthocyanin-based natural dye, used within the wet-spinning process, to reduce the environmental impact of the dyeing process. It is observed that similar or improved dye sorption and much improved 3D sustainability metrics (energy and material intensity) can be achieved through dyeing of casein fibers in flow, with higher color strength ($K/S_{\lambda max}$ = 2.5) observed under milder conditions (room temperature, 10 s) compared to conventional dyeing ($K/S_{\lambda max}$ = 1.0 at 40 °C, 30 min; $K/S_{\lambda max}$ = 2.7 at 80 °C, 30 min). Energy intensity calculations show conventional dyeing requires 1.7−5.0 MJ kg^{-1} fiber, depending on the dyeing temperature for experiments performed in this paper and up to 13.4 MJ kg^{-1} fiber for examples in the literature. Using coloration in flow, energy intensity is negligible showcasing a vast improvement in energy-based metrics. The *in situ* experimental method showed a material intensity of 10.2 compared to 21.2 of the conventional method explored and up to 40.2 for examples in the literature, making the process in flow far less material intensive than conventional coloration methods, with additional potential for further material savings due to the recycling potential of the dyebath, which does not require auxiliary dyeing chemicals. Space time yield calculations showed that the productivity of the proposed method in flow is much higher (182.4 g L^{-1} h^{-1}) compared to the conventional batch process (33.3−60.0 g L^{-1} h^{-1}).



KEYWORDS: *coloration, dyeing, natural dyes, fibers, food waste, anthocyanins, valorization, sustainable processes, wet-spinning, regenerated protein fibers*

INTRODUCTION

Textile production is one of the most environmentally damaging industries on the planet. Global annual fiber production was over 113 million tonnes (Mt) in 2021 and is predicted to increase to 149 Mt by 2030.[1] This increase has a direct impact on the amount of raw materials, energy, and water required for the textile industry with the potential for catastrophic environmental ramifications.

By the implementation of circular design principles, there is potential to help alleviate the issues presented by the vast fiber production of the modern world and reduce the impact of waste from another environmentally important sector: the food industry. Approximately one-third of all food produced in the world is wasted, representing a vast, underutilized feedstock for sustainable chemicals and materials.[2] Regenerated fibers from waste is an area of active research with multiple biopolymers being explored, including the utilization of waste protein to create regenerated protein fibers (RPFs). This approach was used during the world wars to help alleviate material shortages, but there is modern day potential with RPFs offering solutions to global food waste and the environmental impact of fiber production.[3,4]

The textile coloration industry is being scrutinized for its efforts to become more environmentally benign, with regulatory bodies and consumers demanding evidence of reduced energy and water usage within dye phases, as well as increased interest in nonsynthetic dyes.

Anthocyanins are a group of polyphenolic compounds occurring within nature and responsible for pink, red, purple, violet, and blue coloration in fruits, vegetables, and flowers.

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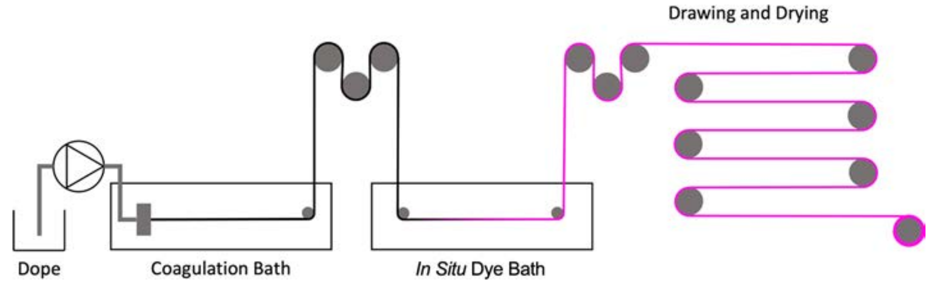

Figure 1. Simplified diagram demonstrating the combined wet-spinning and *in situ* coloration processes for casein fibers.

They are nontoxic, water soluble, and plentiful within many food waste streams, such as pomace from juice and wine production. These compounds are of increasing interest to the sustainable color chemist as a potential substitute for synthetically derived dye compounds.[5−8]

Spin or dope dyeing has been identified as a more sustainable option to produce colored fibers through either melt or wet-spinning.[9] This process has its limitations as only one color of fiber can be produced from the polymer "dope", so the technology is only applied to colors with a large market demand. The economic and process development hurdle of generating new and different colors is large.

During wet-spinning, the dissolved polymer "dope" is extruded into a coagulation bath containing an antisolvent, causing the polymer to solidify into the fiber. This is not instantaneous, and the fiber does not finish forming until it is fully dry. This intermediate form, referred to as "never-dried" fiber, is characterized by a more "open" polymer network caused by the remaining presence of polymer dissolution solvent within the polymer matrix. There is potential to dye the fibers during this phase through inclusion of the dye into the treatment baths of the still-forming fiber, where the dye molecules diffuse more easily through the polymer network. Incorporating the dyeing step into fiber production could reduce the energy and materials required to dye the fibers and be more flexible than dope dyeing.

An *in situ* dyeing process utilizing a novel, modular, lab-scale wet-spinning rig was created to produce kilometer quantities of food waste-derived casein monofilament, dyed with anthocyanins in flow. This was compared to conventionally dyed casein fibers.

EXPERIMENTAL SECTION

Materials. Pure casein from bovine milk and all chemicals were obtained from Sigma-Aldrich. Commercial casein fiber sliver was purchased from George Weil, U.K. Blackcurrant (*Ribes nigrum* L.) pomace was obtained from A&R House, U.K. The dried blackcurrant extract dye powder was produced using the method presented by Farooque et al.[7]

Conventional Dyeing Process. Casein fibers were dyed at pH 2, from 40 to 80 °C, in an aqueous solution with 5% omf (on mass of fiber) blackcurrant dye powder using a liquor-to-fiber ratio of 20:1 using the methodology presented by Blackburn et al.[8] Full details can be found in the Supporting Information (SI).

In-Flow Dyeing Process. The *in situ* dyeing process involved using a novel, lab-scale, modular wet-spinning rig fabricated in-house to wet-spin casein fibers and then immediately dye the still forming fiber in a secondary coloration bath in a flow method. Figure 1 shows a simplified schematic diagram of this process. Full methodology, along with a video (Video S1) showing the process, can be found in the SI.

Color Measurement. Conventionally dyed fibers and fibers dyed in flow were measured using a Datacolor 500 color spectrophotometer as described by Blackburn et al.[8] to determine the color strength at maximum wavelength of absorption ($K/S_{\lambda max}$) and fiber color. Full details can be found in the SI.

Sustainability Metrics. Key 3D sustainability metrics energy intensity and material intensity were selected based on the work of Martins et al.[10] and as used by Xu et al.[11] in their exploration of dyeing PLA. Because of the novel *in situ* dyeing methodology and its similarities to the continuous nature of flow chemistry, a commonly used metric used in flow chemistry, space time yield (STY), was also used as a measure of productivity in g L^{-1} h^{-1}. These metrics were used to compare the novel coloration in flow method to the conventional dyeing method described herein and also to compare with literature examples of dyeing casein fibers with natural dyes[12] and synthetic dyes.[13] Full descriptions of the calculations and assumptions made can be found in the SI.

RESULTS AND DISCUSSION

Colorimetric Analysis. Quantitative colorimetric work was carried out on the commercially sourced, conventionally dyed casein fibers and the *in situ* dyed fibers produced. From dyeing results (Figure 2), it is seen that a similar or greater color strength ($K/S_{\lambda max}$) is achieved from the process in flow under

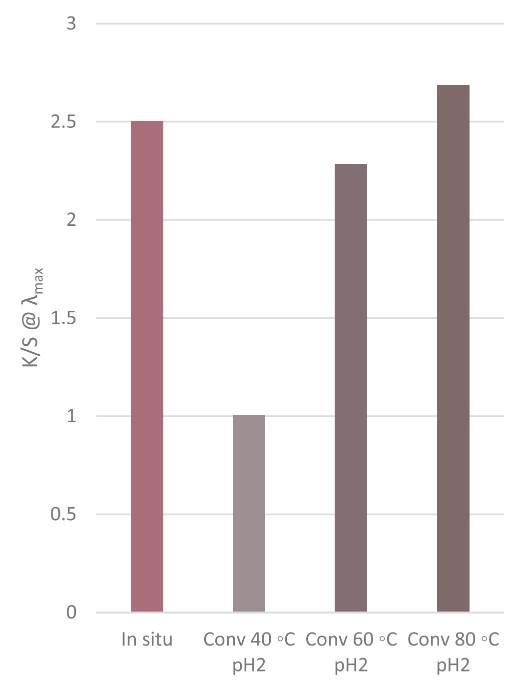

Figure 2. Comparison of color strength ($K/S_{\lambda max}$) between *in situ* and conventional methods. The color of the column represents the color of the dyed fiber.

Table 1. Overview of Sustainability Metrics for Conventional Dyeing vs Coloration in Flow from Both Experimental and Literature Values, with Color Scale Indicating Sustainability Preference

Dyeing Procedure	Material Intensity	Energy Intensity (MJ kg^{-1} fiber)	Space Time Yield (g L^{-1} h^{-1})
New *in situ* Method	10.2	0.0	182.4
Conventional @ 40ºC	21.2	1.7	60.0
Conventional @ 60ºC	21.2	3.4	42.9
Conventional @ 80ºC	21.2	5.0	33.3
Literature Natural Dyes[12]	41.2	13.4	10.7
Literature Synthetic Dyes[13]	20.0	4.6	39.1

ambient conditions compared to conventional dyeing at elevated temperatures, which is unsurprising when the fiber morphology is considered. With conventionally dyed fibers, fiber morphology is compact, and elevated temperatures are required to swell the fiber to allow dye diffusion into the outermost layers. The process in flow means the fiber is dyed seconds after formation while its structure is still very open, allowing easy and swift diffusion of the solution throughout the fiber under milder conditions.

As reported by Blackburn et al.,[8] the form of the anthocyanin heavily influences the resulting color of the dyed fiber. Anthocyanins have three forms, each with distinct colors, depending on the pH of dyeing solution: <pH 3, flavylium cation (**AH**$^+$, red); pH 3−7, quinonoidal base (**A**, purple); pH > 7, anionic quinonoidal base (**A**$^-$, blue). As the pH of the dyebath within the *in situ* dyeing process was highly acidic (due to the required conditions for wet-spinning of casein) the anthocyanin is likely 100% red **AH**$^+$ form. The pH of the conventional dyeing was set at pH 2 to ensure 100% **AH**$^+$ form and to allow for direct comparison. The fiber dyed in flow exhibits a much greater a^* value in CIELab color analysis, indicating a shift toward red compared to the conventionally dyed samples; this is represented in Figure 2, with the color of the dyed fiber denoted by the color of the bar. It is theorized that this is due to much-improved dye penetration during the *in situ* process. After conventional dyeing, during the exhaust process, some of the anthocyanin molecules on the surface of the fiber are likely converted to the neutral or anionic forms of the molecule (characterized by a shift toward a blue color) meaning that the overall hue of the fiber also shifts toward blue. However, anthocyanin molecules diffused inside the fiber are theoretically protected from the aqueous environment and, therefore, retain their pink color. This is further evidenced by an observed shift toward red as the temperature of dyeing is increased, due to the greater dye diffusion found at elevated temperatures.

Process Analysis via Sustainability Metrics. Because of the ease of dye diffusion into "never-dried" casein fibers during the wet-spinning process, it was predicted, and proven, that much milder conditions, reduced material usage, and vastly reduced dyeing times could yield similar or better results in terms of color intensity. This is beneficial from a process-intensification standpoint, as well as improving the sustainability metrics in the dyeing process. Some reasonable calculations for the material intensity, energy intensity, and productivity (as calculated through STY) for each experimental process (along with examples from literature) have been calculated and are summarized in Table 1; full calculations and assumptions made can be found in the SI.

As the process in flow is unheated (room temperature), dyeing energy intensity can be assumed to be negligible, in keeping with literature conclusions for the reduction of energy usage in the LCA of dope-dyeing systems.[9] Overall energy intensity of the conventional dyeing process used herein varied from 1.7 to 5.0 MJ kg^{-1} with varying temperature and was up to 41.2 MJ kg^{-1} for literature examples; in comparison, the energy intensity for coloration in flow is effectively zero. Material intensity for conventional dyeing processes (21.2 to 41.2) is substantially higher than for the *in situ* process (10.2). The productivity of the process reduces with increasing fiber:liquor ratio (as more volume is required to make the same mass of colored fiber) and with elevated temperature (as the time taken to reach the temperature increases). The conventional batch methods used herein show STYs of 33.3−60.0 g L^{-1} h^{-1}, with STY as low as 10.7 g L^{-1} h^{-1} in literature methods, all of which are far lower than for the novel flow method (182.4 g L^{-1} h^{-1}). All three metrics demonstrate that the coloration method in flow is an improvement over conventional exhaust dyeing processes in terms of energy intensity, material intensity, and productivity.

Additionally, the potential to recycle the dyebath is far greater with the *in situ* process compared to the conventional process. In the conventional process, the exhausted dyebath still exhibits intense color, presenting an inherent dye waste issue for effluent. Dyebath recycling in the conventional process is complicated by the auxiliaries chemicals present, which is not an issue for the *in situ* process. Within the conventional dyeing presented in this work, pH modifiers were the only auxiliaries used, but in industrial dyeing, there would be many more: dispersion agents, wetting agents, leveling agents, etc., which would lead to complications for dyebath recycling.[14] Due to the increased dye penetration observed in the *in situ* process, these auxiliaries are likely not required, and the process, as it is continuous, exhibits much greater potential for bath recycling. If dye concentration was monitored throughout the spinning process (e.g., using UV−vis spectroscopy) and "topped up" when it reached unacceptably low levels, the dyebath could potentially be recycled indefinitely. In practice, this would likely not be possible as eventually the pH would be altered by any residual solvation agent present in the fiber, but as the dyeing step comes after the initial coagulation step (during which most of the polymer solvent is removed), this effect is likely to be small.

One major disadvantage of dope dyeing is the need to shut down and completely clean the entire spinning system if a new fiber color is required due to the colorant being added into the polymer dope and therefore present throughout the system. The novel *in situ* process completely removes the need for this as an uncolored polymer dope is used with an *in situ* dye bath, which could easily be swapped out for a different bath with a different coloration agent as required, making the *in situ* process more widely applicable to the coloration industry than dope dyeing.

Limitations of the Coloration In-Flow System. Initial evidence indicates improvements that fiber coloration in flow could have over conventional dyeing systems, but there are limitations to consider when designing such a system. Dyeing conditions are limited to the fiber spinning process conditions. As the fiber has not yet finished solidifying, it is susceptible to any solvent and pH too similar to the original solvation agent: dyeing conditions must be suitable to keep the fiber solid during the process. This would limit the dyes that could be used within the process as they would have to be effective under, and resistant to, these conditions. This issue could potentially be circumvented by adding a cross-linking step before dyeing, but this would complicate the process. It also limits the conditions to those applicable to wet-spinning. Blackburn et al.[8] reported that the optimal pH for dyeing of casein fibers with anthocyanins was pH 4, represented by a 60:40 ratio between the **A** and **AH**$^+$ forms, respectively, but this was not possible in this particular in-flow process. So all comparisons within this paper are with dyeing at pH 2 (closest to the conditions used *in situ* and 100% **AH**$^+$). For fibers dyed under optimal conditions using conventional exhaust processes (pH 4, 80 °C, 30 min), $K/S_{\lambda max}$ was 3.5, slightly higher than observed for the *in situ* process; however, for exhaust dyed fibers at lower temperatures (pH 4, 40 °C), closer to those of the *in situ* process (room temperature), lower $K/S_{\lambda max}$ (1.5) was observed, indicating that the *in situ* process is far more effective at lower temperatures (and shorter dyeing times) even when exhaust dyed at optimal pH. In other work, it was observed that color strength of proteinaceous fibers (hair) dyed with anthocyanins increases with increasing dye loadings, up to $K/S_{\lambda max}$ of 11.7,[15] implying that the limit for color strength through dye penetration has not been reached in the work herein. Therefore, there is potential for the color strength of *in situ* dyed fibers to be increased above those achieved with the optimal exhaust dyeing conditions by increasing the dye loading in the process.

■ CONCLUSIONS

This study has explored the potential for *in situ* dyeing of wet-spun fibers as a less environmentally impactful method of coloration. Including a coloration bath in the wet-spinning process alleviates many known issues around dope dyeing while dramatically improving key sustainability metrics such as energy intensity, material intensity, and productivity. The evidence from the colorimetric analysis of the produced fibers indicates *in situ* dyeing is more effective, likely due to the ease of dye penetration in the forming fiber's more open polymer network. This allows for more effective dyeing under gentler conditions and could also potentially remove the need for dye auxiliaries, making the recycling of the dyebath by simple addition of more dye a possibility. There is much research to do in developing this proof-of-concept study to industrial relevance, but the possibilities for reducing the environmental footprint of the textile industry is huge.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssuschemeng.3c07437.

Video S1: Novel *in situ* coloration method described herein (MOV)

Overview of experimental methodology and metric calculations and assumptions made (PDF)

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Notes

The authors declare no competing financial interest.

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