Catalyst Report on Circular Fashion & Textiles

The Provision of Research Relating to Environmental Science for Circular Fashion and Textiles

ual: fashion, textiles and technology institute

Natural Environment Research Council

Catalyst Report on Circular Fashion and Textiles — The Provision of Research Relating to Environmental Science for Circular Fashion and Textiles

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Glossary

CF&T: Circular Fashion and Textiles (including all associated production and recovery technologies and services within the fashion and textiles ecosystem)
Fast fashion: Short-life, inexpensive clothing produced rapidly by mass-market retailers
FMCG: Fast Moving Consumer Goods
FTT: Fashion, Textiles and Technology
EOL: End of Life
EPR: Extended Producer Responsibility
LCA: Life Cycle Assessment
MRSL: Manufacturing Restricted Substances List
PEF: Product Environment Footprint
TRL: Technology Readiness Level
s-LCA: Life Cycle Assessment including social factors
ZDHC: Zero Discharge of Hazardous Chemicals

This report has been delivered by UAL's Fashion, Textiles and Technology Institute (FTTI), founded to deliver sustainable innovation across the entire fashion, textiles and technology value chain. It employs a whole-systems approach to global challenges including climate change, ethics and labour, and the Circular Economy. The team includes experts in environmental chemistry, circular design, fashion business and management as well as technical textiles.

Professor Kate Goldsworthy — Principal Consultant. Kate has worked in the field of Circular Fashion and Textiles at the intersection of design, material science and engineering since 2006. As Chair of Circular Design and Innovation and Co-Director of UAL's Centre for Circular Design, her research focus over the past decade has been in the alignment of environmental science and circular design practice through transdisciplinary research. This has included EU consortium projects (Trash-2-Cash 2015-2018; Mistra Future Fashion 2015- 2019; and HEREWEAR, 2020-2024). Kate is Deputy Director and Co-Investigator on the UKRI Business of Fashion, Textiles and Technology (BFTT) Creative R&D Partnership (CRDP), involving R&D with multiple UK-based SMEs to progress circular and sustainable technology innovation in the FTT sector.

Professor Jane Harris — Senior Consultant. Jane is Director of the UAL FTTI, providing leadership of transdisciplinary research and development initiatives aligned to the new UAL campus (2023), as part of the East Bank, Stratford development. Jane is Chair of Digital Design & Innovation, and the Principal Investigator of the £5.5 million Business of Fashion, Textiles and Technology Creative R&D Partnership (£2018-23) — achieving £16 million in co-investment to date and focused on delivering industry-led sustainable innovation within the fashion and textiles supply chain.

Professor Mohammad Mahbubul Hassan — Senior Consultant. Mohammad is a Chair in Advanced Sustainable Materials Science, with 25 years of academic and industrial research experience in sustainable textile and polymeric materials development, and expertise in sustainable textiles, biodegradable polymeric materials and eco-friendly multi-functional textiles. Mohammad holds a PhD in Textile Chemistry and for 18 years has worked as a senior scientist in the Bioproduct and Fibre Technology Team of the New Zealand Pastoral Agricultural Research Institute.

Laura Solomon — Consultant. Laura is an R&D Fellow in Textile Science and Technology at the UAL FTTI, where she works at the interface of the fashion, textiles and technology industries, higher-education research and knowledge exchange to shape the R&D agenda. She has a background in textile R&D and manufacturing facilities, working on product development and leading textile science R&D projects — including with the British Council, UK and ODA country partners.

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1 Executive Summary

Develops technologies for extraction and refining of natural dye colours

This report presents the results of an assessment of environmental science research activity that is specific to Fashion, Textiles and Technology needs and opportunities to inform a cross-UKRI intervention on the topic of **Circular Fashion and Textiles** (CF&T).

It is estimated that the fashion and textile industrial sector produces up to 10 percent of all global CO2 emissions each year, while also being the second largest water consumer globally. Research has reported estimations that this industry produces approximately 93.1 million tonnes of textile waste annually, which either ends its life in landfills or incineration.[1] Additionally, research has found that under 1 percent of the textiles manufactured for application in the broader apparel industry is later recycled into new garments, and 87 percent of the materials used for apparel manufacture is either landfilled or incinerated after their definitive use.[2]

The principal tenet of Circular Economy (CE) is to achieve a fashion and textiles industry with reduced absolute use of resources, by designing products, materials and process systems that allow retention of materials for future use. CE principles are essential to the development of circular fashion, and the wider apparel and textiles systems that aim to preserve resources and achieve the net-zero targets and reduction of other environmental impacts.

However, the global fashion and textiles industry, with which the UK intersects, is complex. All elements of the global value chain need to be examined and reviewed, in order to address the most significant environmental issues at scale. This includes the socio-cultural and psychological motivations of consumption within a dominant volume-growth logic system.

The challenges and recommendations from the FTT industry are largely agreed and evidenced through several key reports (2020–2022), see **Section 8.3**. This report attempts to situate these recommendations within an environmental science context, while addressing the most pressing industry challenges.

While all five research themes would underpin a CF&T paradigm, they are not all equal in terms of priority, urgency and relevance to National Environment Research Council research areas.

- **4.1 Supply Chain Impact Reduction**
- **4.2 Fibre and Chemical Loss**
- **4.3 Innovative Fibre and Recycling Technologies**
- **4.4 Circular Design and Business Models**
- **4.5 Interdisciplinary Research Methods**

See prioritisation matrix and rationale (**Section 4**) and Theory of Change (**Section 5**).

1 Quantis (2018) Measuring Fashion: Insights from the Environmental Impact of the Global Apparel and Footwear Industries Study. Full report and methodological considerations. Available at: https://quantis-intl.com/report/measuring-fashion-report

2 Ellen MacArthur Foundation (2017) A New Textiles Economy: Redesigning fashion's future. Available at: https://ellenmacarthurfoundation.org/a-new-textiles-economy

The most relevant themes and prioritised research questions for environmental science research are summarised in the conclusion (**Section 7**). The future FTT industry, and the environment, depend on the early alignment of apparel, textiles and environmental science disciplines to work on complex systems issues and new methodologies. Better use of data, stakeholder engagement and interdisciplinarity are also required to begin to address the scale of the challenges the industry is facing.

1.1 Validated environmental data

This research has concluded that by far the biggest challenge for the FTT industry is to establish standardised and universally agreed data to inform decision-making and avoid regrettable substitutions. The fashion, apparel and textiles industries are poised and prepped for action and have committed to COP26, including the employment of data analysts and environmental scientists in their sustainability teams in some cases. A proliferation of new data-technology start-ups are developing the tools to translate data to the brands in a compelling and meaningful way. However, the data itself is splintered and contestable with no firm standardisation or regulatory framework, although this is beginning to be addressed by WRAP / DEFRA, which are currently developing policy recommendations on this topic.
This relates to themes 4.1.b, 4.2.a, 4.3.a, 4.3.b, 4.4.a.

1.2 Fibres and chemicals in the environment

The second most important challenge determined by the stakeholder engagement is the behaviour and damage to the environment caused by fibres (and associated chemicals). In order to fill knowledge gaps in this area, further research should include testing under real-life conditions including soil, freshwater, air and ocean environments, and with relevance to the most commonly used fibre blends and chemical combinations. This includes issues of toxicity as well as irritation to wildlife and human ingestion. Increasing research into biodegradation, and also fibre recovery, would be beneficial.
This relates to themes 4.2.a, 4.2.b, 4.3.a, 4.3.b.

1.3 Interdisciplinarity and environmentally informed design

Integrating environmental science research into the earliest possible stages of product development is an essential but currently limited practice. More work is needed to study how the particular characteristics of fashion and textile design research, materials science research, and LCA research can be integrated. The scientific theory and development behind the design research process, and the environmental science research process have synergies. The challenge is to combine these processes into a singular and interrelated approach. If best practice principles can be established and proven through research in areas outlined in (1) and (2), embedding them into a proactive design, decision-making context is essential to reach maximum impact in the time frame required to meet net zero and achieve climate change objectives set during 2021/2022, with effect by 2030.
This relates to themes 4.1.b, 4.2.b, 4.3.a, 4.3.b, 4.4.a, 4.4.b, 4.5.a

2
Approach

Producer of Made to Measure sustainable denim

Primary and secondary research was conducted involving engagement with stakeholders from across CF&T and environmental science — industry and academia. The research outputs informing the report are summarised below.

2.1 Secondary research sources

→ **Output 1: Landscape report — See Section 3**
Literature review spanning over **150 academic publications (UK-authored)**, a further **300 publications (international)**, and **20 relevant industry reports.**

Database of relevant UK research initiatives including over **50 projects and programmes** from across the UK Research and Innovation (UKRI) funding councils: the Natural Environment Research Council (NERC), the Biotechnology and Biological Sciences Research Council (BBSRC), the Engineering and Physical Sciences Research Council (EPSRC), the Arts and Humanities Research Council (AHRC), the Economic and Social Research Council (ESRC), Innovate UK, and relevant international funding bodies, private and third-sector funding.

2.2 Primary research sources

→ **Output 2: Analysis of key market failures — See Section 3**
140 stakeholders (90 academic researchers and **50 industry leaders)** were identified, of which 30 provide insight from across the textile value chain aligned to lifecycle sectors

- where environmental science research is not currently addressing said market failures outlining funding gaps/opportunities to do so
- where pre-competitive opportunities exist, which may be addressed through environmental science.

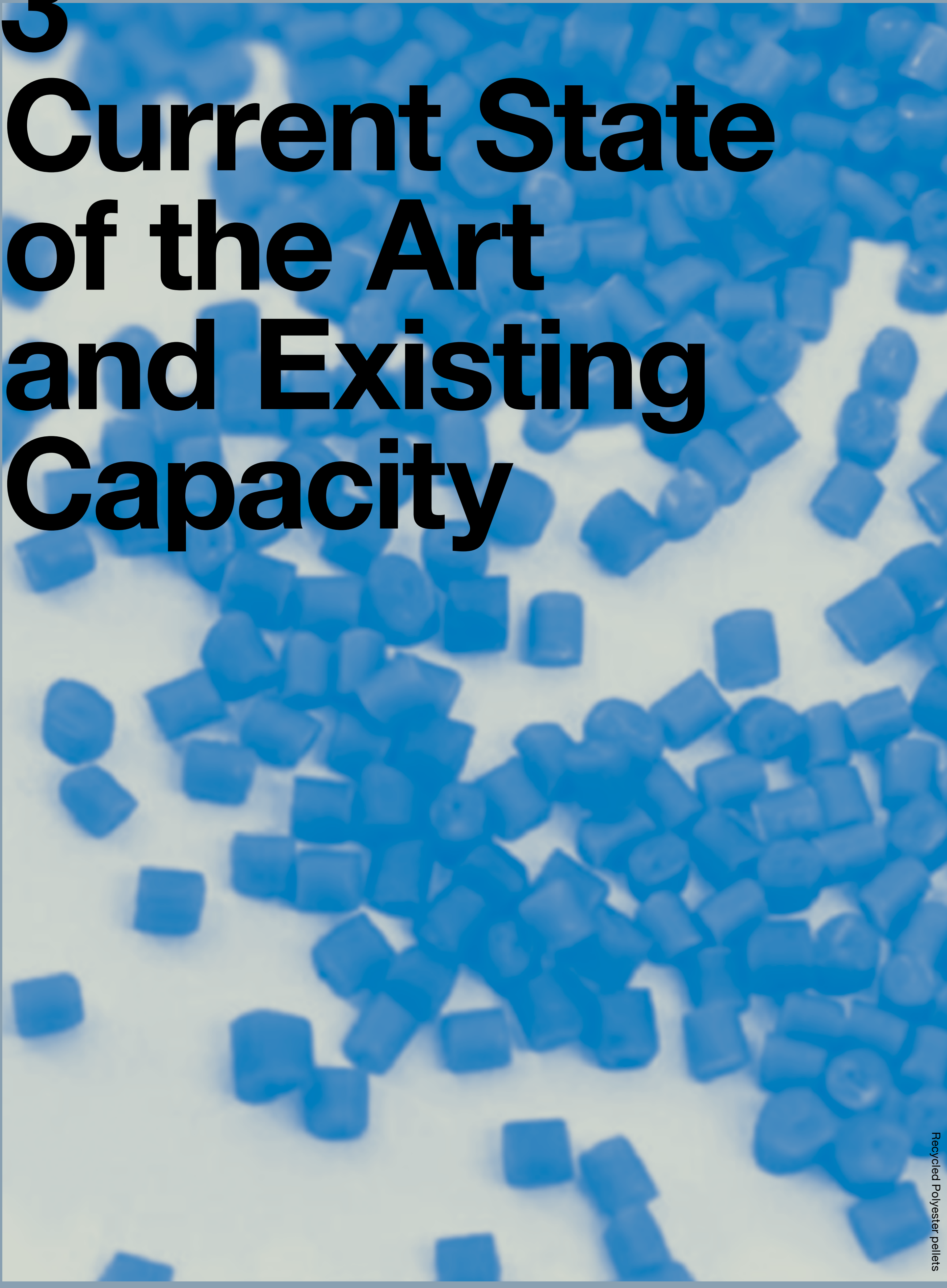
→ **Output 3: Environmental science research areas — See Section 4**
The environmental science research areas (and associated research themes and questions) and types of intervention (e.g. programme funding, pump-priming pilots, training programmes — see Section 4) which may transform the sector.

→ **Output 4: Logic model or theory of change — See Section 5**
A logic model or theory of change illustrates how public investment in priority areas (as outlined in Output 3) would deliver tangible benefits to the UK, also taking into account:

- the impact of Covid-19 and other environmental, social and political shocks
- significant opportunities to facilitate a green recovery
- benefits to the UK fashion, wider apparel and textile economy specifically.

→ **Output 5: Overview of emerging trends — See Section 6**
Emerging environmental, political, social or technological trends that may advance the development of a circular fashion, apparel and textile economy over the longer term are identified, including:
- potential headwind and tailwind disruptors
- articulation of prospective research programmes.

3
Current State of the Art and Existing Capacity



Recycled Polyester pellets

3.1 Landscape review summary

At the core of the fashion, apparel and textiles industry, and a particular environmental challenge, is the trillion-pound global fibre industry, which is also of strategic importance to the UK economy. Textile products for clothing, soft furnishings, and nonwovens (sanitary products, wet wipes, face masks, medical items) are made from just a few source materials, primarily cotton and polyester.[3] A tonne of textile waste is discarded in the UK every minute, a consequence of the related levels of consumption that accompany the development and promotion of new products.[4, 5, 6]

An estimated 1.3 billion tonnes of greenhouse gases are released from textile production, manufacturing, and disposal worldwide every year.[7] Microfibres (both synthetic polymers and cellulosics) released during the lifetime of fibre-based products account for over a third of all plastic reaching the open ocean, threatening both the environment and human health.[8] Disposal of wet wipes and other hygiene items exacerbates sewer 'fatbergs', a problem that has grown exponentially with the increased public use of PPE due to Covid-19.[9, 10]

The fibres industry has stressed the urgent need for solutions-based research and development in order to reduce the environmental footprint of fibres across their lifecycle, to create new business opportunities, to support design, business and technical innovations, and to protect scarce natural resources. This requires a systematic approach, drawing on the wide range of expertise within the UK in fibre technologies, environmental science, design and anthropology, to circularise the resource flow for fibres in the UK and recalibrate consumption habits.

Interventions are needed to address systematically the accumulation, impact and heavy costs to the environment of key synthetic and renewable fibre resource flows. This would support a move away from the current linear system, while maintaining and supporting applications of fibres for multiple high-value purposes. Other related material resource issues, in particular plastics, also require a similar approach: this is arguably more achievable because of the more advanced regulatory landscape and consumer understanding of plastics recycling.

3 Textile Exchange (2018) Preferred Fiber & Materials Market Report. Available at: https://store.textileexchange.org/wp-content/uploads/woocommerce_uploads/2019/04/2018-Preferred-Fiber-Materials-Market-Report.pdf
4 Jha, A.K., et al. (2008) Greenhouse gas emissions from municipal solid waste management in Indian mega-cities: A case study of Chennai landfill sites, *Chemosphere*, 71:750. Available at: https://doi.org/10.1016/j.chemosphere.2007.10.024
5 Labfresh (2020) The Fashion Waste Index. Available at: https://labfresh.eu/pages/fashion-waste-index?lang=en&locale=en
6 Quantis (2018) Measuring Fashion: Insights from the Environmental Impact of the Global Apparel and Footwear Industries Study. Available at: https://quantis-intl.com/report/measuring-fashion-report/
7 Jha, A.K., et al. (2008) Greenhouse gas emissions from municipal solid waste management in Indian mega-cities: A case study of Chennai landfill sites, *Chemosphere*, 71:750. Available at: https://doi.org/10.1016/j.chemosphere.2007.10.024
8 Sanchez-Vidal, A., et al. (2018) The imprint of microfibres in southern European deep seas, *PLoS One*, 13 (11), e0207033. Available at: https://doi.org/10.1371/journal.pone.0207033
9 RICS (2021) Anatomy of a fatberg: can our sewers cope? Available at: https://ww3.rics.org/uk/en/modus/built-environment/resilient-infrastructure/anatomy-of-a-fatberg--can-our-sewers-cope-.html
10 Porter Jr., G. (2021) 'America's Obsession With Wipes Is Tearing Up Sewer Systems', *Bloomberg* (26 March). Available at: https://www.bloomberg.com/news/articles/2021-03-26/pandemic-wipes-create-sewer-clogging-fatbergs

Effects of textile fibres and chemicals on ecosystems, conservation and biodiversity

The textile industry is one of the greatest environmental polluters.[11, 12] The production of synthetic and natural fibres has a high environmental impact.[13] As most synthetic fibres are produced from fossil fuel-based feedstocks, they cause natural resource depletion.[14] On the other hand, the production of some natural fibres (e.g. cotton) has even higher environmental impacts than the production of synthetic textiles, because of the utilisation of huge quantities of pesticides and fertilisers, and also extensive land use, which leads to a high impact on natural ecosystems and human health.[15, 16] Textile dyeing, printing, and finishing industry effluent are great concerns, as they produce highly coloured effluent containing dyes and other textile auxiliaries. A variety of chemicals and polymers are used in the pre-treatment, dyeing, printing, and finishing of textile products.[17]

Cotton textiles

Although cotton is an extremely popular textile fibre, and is the second largest fibre quantity used in textile production after polyester, it is known to be the dirtiest crop. In the US alone, pesticides worth $4.2 billion were used in cotton cultivation in 2017, alongside a huge quantity of fertilisers, according to the US Department of Agriculture (USDA);[18] in the same year, 21.8 million kg of pesticides were used on 12.6 million acres of cotton cultivation (equivalent to 1.73kg pesticide/acre) in nine states.. Insecticides, nematicides, fungicides, herbicides, desiccants and defoliants used in cotton fibre production have been associated with many environmental and health issues[19, 20] including those caused by toxic pesticides that end up in cotton fibre desizing and processing effluent.

Warp cotton yarns are treated with various sizing agents, including starch, polyvinyl alcohol, carboxymethyl cellulose, polyvinyl alcohol and acrylic copolymers, water-soluble polyesters, etc., to strengthen the yarns and prevent yarn entanglement, improving the weavability. However, for uniform dyeing and finishing, they need to be removed by a process called desizing. As a result, these sizing agents are released as effluent. Some of these sizing agents (e.g. acrylic copolymer) may not biodegrade in the environment.[21] Cotton fabric scouring effluent contains a high quantity of alkali,

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11 Gbolarumi, F.T., et al. (2021) Sustainability Assessment in The Textile and Apparel Industry: A Review of Recent Studies*, IOP Conference Series: Materials Science and Engineering*, 1051 012099. Available at: https://iopscience.iop.org/article/10.1088/1757-899X/1051/1/012099/pdf

12 Quantis (2018) Measuring Fashion: Insights from the Environmental Impact of the Global Apparel and Footwear Industries Study. Available at: https://quantis-intl.com/report/measuring-fashion-report/

13 Stanton, T., Johnson, M., Nathanail, P., MacNaughtan, W., and Gomes, R.L. (2019) Freshwater and airborne textile fibre populations are dominated by 'natural', not microplastic, fibres, *Science of The Total Environment,* 666. Available at: https://doi.org/10.1016/j.scitotenv.2019.02.278

14 Tuladhar, R., and Yin, S. (2019) 21 - Sustainability of using recycled plastic fiber in concrete, *Use of Recycled Plastics in Eco-efficient Concrete*, pp.441–460. Available at: https://doi.org/10.1016/B978-0-08-102676-2.00021-9

15 Chen, F., Ji, X., Chu, J., Xu, P., and Wang, L. (2021) A review: life cycle assessment of cotton textiles, *Industria Textila*, *Special issue on Circular Economy*, pp.19–29, Available at: https://doi.org/10.35530/it.072.01.1797

16 Kazan, H., Akgul, D., and Kerc, A. (2020) Life cycle assessment of cotton woven shirts and alternative manufacturing techniques, *Clean Technologies and Environmental Policy*, 22, pp.849–864. Available at: https://doi.org/10.1007/s10098-020-01826-x

17 Yaseen, D.A., and Scholz, M. (2019) Textile dye wastewater characteristics and constituents of synthetic effluents: a critical review, *International Journal of Environmental Science and Technology*, 16, pp.1193–1226. Available at: https://doi.org/10.1007/s13762-018-2130-z

18 U.S. Department of Agriculture (2018) Agricultural chemical use program. Available at https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/

19 Blackburn, R.S. (2009) *Sustainable textiles life cycle and environmental impact*. Woodhead Publishing in Textiles.

20 Settle, W., et al. (2014) Reducing pesticide risks to farming communities: cotton farmer field schools in Mali, *Philosophical Transactions of the Royal Society*, B, 369, pp.1–11.

21 Gaytán, I., Burelo, M., and Loza-Tavera, H. (2012) Current status on the biodegradability of acrylic polymers: microorganisms, enzymes and metabolic pathways involved, *Applied Microbiology and Biotechnology*, 105, pp.991–1006. Available at: https://doi.org/10.1007/s00253-020-11073-1

detergents, and other textile auxiliaries.[22, 23]

Cotton fibres are mostly dyed with reactive dyes and up to 45 percent of the applied dyes are hydrolysed, making them non-reactive to cotton textiles, so they end up in the dyeing effluent.[24] Cotton fibres can be dyed with natural dyes, but poor colourfastness to light and washing[25] has limited their application for cotton dyeing. Technological advancement is needed to address the issue of dyeing textiles with natural colourants, as very few recent studies have been carried out to address these issues. Pre- or post-mordanting treatment with metallic salts considerably improves the colourfastness to washing; the mordanting agents used, however, are mostly toxic heavy metals, including chromium, copper and aluminium. Natural dyes are biodegradable, but the biodegradation of dyes releases heavy metals into the environment. These heavy metals are known to bioaccumulate, increasing the danger to human health.[26]

Cotton and other cellulosic fabrics are prone to wrinkle formation and are therefore treated with various formaldehyde-releasing prepolymers. This not only causes liberation of formaldehyde during processing, but also during use.[27] For the curing of these prepolymers, various metallic salts are used, which may end up in effluent. As well as dyes, cotton printing also uses various natural and synthetic polymers as thickeners for the preparation of printing paste, and these are removed during post-printing washing. Other than wrinkle-resist treatment, cotton fabrics are treated with organic and metallic nanoparticle-based antimicrobial agents, acid-liberating metallic salts, UV absorbers, fire-retarding chemicals, and water-proofing chemicals (including fluorocarbon polymers). Most of these are toxic and/or hazardous and their release into the environment can have unprecedented impacts on aquatic and soil ecosystems, and on human health.[28, 29, 30, 31, 32]

Various coating and pigment formulations used in the textile industry use solvents and other organic volatile compounds, and their release into the factory environment could be harmful to workers.[33] C8-based fluorocarbons are popular for making textiles waterproof, but C8-based fluorocarbon formulations contain carcinogenic perfluorooctanoic acid (PFOA) or

22 Madhav, S., Ahamad, A,. Singh, P., and Kumar Mishra, P. (2018) A review of textile industry: Wet processing, environmental impacts, and effluent treatment methods, *Environmental Quality Management*. Available at: https://doi.org/10.1002/tqem.21538
23 Correia, V.M., Stephenson, T., and Judd, S.J. (1994) Characterisation of textile wastewaters — a review, *Environmental Technology*, 15:10, pp.917–929. Available at: https://www.doi.org/10.1080/09593339409385500
24 Gopalakrishnan M., Shabaridharan, K., and Saravanan, D. (2018) Low Impact Reactive Dyeing Methods for Cotton for Sustainable Manufacturing, *Sustainable Innovations in Textile Chemistry and Dyes*. Available at: https://doi.org/10.1007/978-981-10-8600-7_1
25 Islam, S., Alam, S.M.M., and Akter, S. (2020) Investigation of the colorfastness properties of natural dyes on cotton fabrics, *Fibers and Textiles*, 27(1).
26 Andrady, A.L. (2011), Microplastics in the marine environment**,** *Marine Pollution Bulletin*, 8, pp.1596–1605.
27 Solt, P., Konnerth, J., Gindl-Altmutter, W., Kantner, W., Moser, J., Mitter, R., and van Herwijnen, H. W. G. (2019) Technological performance of formaldehyde-free adhesive alternatives for particleboard industry, *International Journal of Adhesion and Adhesives*, 94. Available at: https://doi.org/10.1016/j.ijadhadh.2019.04.007
28 Jain, A.K., Tesema, A.F., and Haile, A. (2019) Development of shrink resistance cotton using fluorocarbon. *Fashion and Textiles*, 6, 1. Available at: https://doi.org/10.1186/s40691-018-0160-2
29 Chowdhury, K.P. (2018) Impact of Different Water Repellent Finishes on Cotton Double Jersey Fabrics, *Journal of Textile Science and Technology*, 4, pp.85–99. Available at: https://doi.org/10.4236/jtst.2018.43006
30 Emam, H.E., and Bechtold, T. (2015) Cotton fabrics with UV blocking properties through metal salts deposition, *Applied Surface Science,* 357. Available at: https://doi.org/10.1016/j.apsusc.2015.09.095
31 Boateng, J., and Catanzano, O. (2020) *Therapeutic Dressings and Wound Healing Applications*, John Wiley and Sons. Available at: https://doi.org/10.1002/9781119433316.ch8
32 Joshi, M., and Bhattacharyya, A. (2011) Nanotechnology — a new route to high-performance functional textiles, *Textile Progress*, 43:3, pp.155-233. Available at: https://doi.org/10.1080/00405167.2011.570027
33 Claudio, L. (2007) Waste couture: Environmental impact of the clothing industry, *Environmental Health Perspectives*. Available at: https://doi.org/10.1289/ehp.115-a449

perfluorooctanoic sulfonate (PFOS), which are produced as by-products. The development of C4- and C6-based fluorocarbon finishing agents substantially reduced the formation of PFOA/PFOS, but compromised waterproofing performance.[34]

Wool textiles

Wool fibre production also has reasonably high environmental impacts, but compared to cotton production impact is considerably lower.[35] Various hazardous agrichemicals and pesticides, such as organochlorines, organophosphates, pyrethroids, nicotinoids, triazine-based compounds, etc., are used as insect growth regulators and ectoparasiticides to prevent flystrike, and also for remedial treatment of acute conditions, such as in the event of an injury.

Although a recent study shows that the residual pesticide level in clean wool has decreased over the years due to advances in scouring technology,[36] the application of these pesticides and their content in scouring effluent has not decreased. Wool scouring effluent contains a large amount of wool grease, fats, suint and pesticides, and residual pesticides in the fibre may be released into the environment after their end-of-life disposal.[37]

Wool fibre surface has unidirectional scales, which causes permanent felting shrinkage, affecting the appearance and usability of wool-made garments. To prevent felting shrinkage, wool fibres are shrink-resist treated. The most effective and popular shrink-resist treatment is the chlorine-Hercosett process, whereby the hydrophobic layer of wool fibre surface is removed, and the scale edges are smoothed by chlorination and then further coated with a synthetic polyamide resin. A range of alternatives,[38] including treating with bromelain[39] and protease enzyme,[40] have been studied, but as yet none of them can match the shrink-resist performance provided by the chlorine-Hercosett treatment.[41]

As a natural protein fibre, wool fibres are very prone to insect and bacterial attacks, which compromises their long-term usability and appearance. Wool fibres are usually dyed with acid dyes at the boil, an energy-hungry process which also damages the fibre to some extent. To achieve improved wash fastness and brilliant colour, wool fabrics are treated with metal complex dyes;[42] the dyes are complexed with copper, chromium and other metals, to make the dye molecules water-insoluble. Although no formal study has

34 Schellenberger, S., Gillgard, P., Stare, A., Hanning, A., Levenstam, O., Roos, S., and Cousins, I.T. (2018) Facing the rain after the phase out: Performance evaluation of alternative fluorinated and non-fluorinated durable water repellents for outdoor fabrics, *Chemosphere*, 193. Available at: https://doi.org/10.1016/j.chemosphere.2017.11.027

35 Wiedemann, S., Biggs, L., Nebel, B., et al. (2020) Environmental impacts associated with the production, use, and end-of-life of a woollen garment, *International Journal of Life Cycle Assessment*, 25, pp.1486–1499. Available at: https://doi.org/10.1007/s11367-020-01766-0

36 Ranford, S., et al. (2022) Chemical residue trends for Australian and New Zealand wool, *Scientific Reports*, 12, p.768.

37 Shaw (1994), Agricultural chemicals in raw wool and the wool textile industry, *Water and Environment Journal*, 8, pp.287–290.

38 Kadam, V., Rani, S., Jose, S., Shakyawar, D.B., and Shanmugam, N. (2021) Biomaterial based shrink resist treatment of wool fabric: A sustainable technology. *Sustainable Materials and Technologies*, 29, p.e00298.

39 Kaur, A., and Chakraborty, J.N. (2015) Controlled eco-friendly shrink-resist finishing of wool using bromelain, *Journal of Cleaner Production*, 108 Part A. Available at: https://doi.org/10.1016/j.jclepro.2015.07.147

40 Hassan, M.M. and Carr, C.M. (2019) A review of the sustainable methods in imparting shrink resistance to wool fabrics. *Journal of Advanced Research*, 18, pp.39–60. https://doi.org/10.1016/j.jare.2019.01.014

41 Hassan, M.M. and Carr, C.M. (2019) A review of the sustainable methods in imparting shrink resistance to wool fabrics. *Journal of Advanced Research*, 18, pp.39–60. https://doi.org/10.1016/j.jare.2019.01.014

42 Chakraborty, J.N. (2011) 13 - Metal-complex dyes, *Handbook of Textile and Industrial Dyeing,* 1, pp.446-465, https://doi.org/10.1533/9780857093974.2.446

been carried out, it can be expected that wool fabric treated with metal complex dye, when discarded into the environment, will release these toxic metals as the fibres degrade. Synthetic pyrethroids are extensively used in the wool industry to protect wool garments and floor coverings from moth and other insect attacks. Wool fabrics have some natural fire-retardancy that is more effective than that of most other textile fibres, but for some applications, fire-retarding treatments are needed. For this purpose, wool fibres are treated with titanium hexafluorozirconate — the Zirpro process. The discharged effluent contains hazardous absorbable organohalogens (AOX).[43] To date, no alternative fire-resistance treatment has been developed that matches the fire retardancy provided by Zirpro-treated wool.

Synthetic textiles

The production of synthetic textiles may on the surface have lower environmental impacts compared to the global commercial and high volume production of cotton, wool and other 'natural' fibres. Nevertheless, the microplastics that derive from polyester and other synthetic textiles are problematic and compromise the quality of the environment, ecosystems and biodiversity in different ways that are particularly challenging. Conventional PET-based polyester creates pollution along its entire value chain, during the production, use and end-of-life phases, and also contributes to the unsustainable depletion of resources, alongside the impact on land, water, air, ecosystems and human health.[44]

Polyester can be easily dyed using disperse dye with a dispersing agent and acetic acid. Almost 100 percent dye exhaustion can be achieved and the rest of the unexhausted dye can be easily separated from the effluent, as disperse dyes are water-insoluble. Polyester dyeing is very energy-intensive, as it is dyed at 130 to 140°C under high pressure,[45] whereas all other fibres are dyed at a maximum of 98°C at normal atmospheric conditions. Additionally, polyester fabrics need fewer finishing treatments than natural fibres.

Regenerated cellulosic and protein fibres

Regenerated cellulosic fibres (cellulose II) are made from cellulose solution by the wet spinning process. The traditional viscose fibre production process is harmful, as it uses carbon disulfide to convert cellulose to cellulose xanthate, which is soluble in alkali and enables the wet spinning. In the 1980s, Courtaulds developed the lyocell fibre spinning process. Lyocell is a regenerated cellulose fibre made from wood cellulose, using N-methyl-morpholine-N-oxide as a solvent, and is a closed-loop production process.

To date, alternative solvents including ionic liquids have been studied, but none of these processes have produced fibre that has strength similar to the lyocell process developed by Courtaulds.[46] BASF developed an ionic

43 Lewis, D.M. (2013) 'Ancillary processes in wool dyeing' in Lewis, D. M., and Rippon J. A. (eds.) *The Coloration of Wool and other Keratin Fibres.* John Wiley and Sons and Society of Dyers and Colourists, p.99.
44 Palacios-Mateo, C., et al. (2021), Analysis of the polyester clothing value chain to identify key intervention points for sustainability, *Environmental Sciences Europe*, 33, 2.
45 Kale, R.D., Kane, P., Arora, K., and Pradhan, S. (2014) Dyeing of Polyester Using Crude Disperse Dyes by Nanoemulsion Technique, *International Journal of Scientific Engineering and Technology*, 3(2), pp.133–138.
46 Borbély, É. (2008) Lyocell, the new generation of regenerated cellulose, *Acta Polytechnica Hungarica*, 5(3), pp.11–18.

liquid-based regenerated cellulose spinning process, but the ionic liquid that remained within the fibre greatly affected the strength of the produced fibre. Many of these ionic liquids are also harmful and the developed process may have high environmental impacts, as well as potentially impacting human health.[47]

Regenerated protein fibres have also been developed from milk-derived casein, however the resulting fibres are crosslinked with harmful formaldehyde,[48] currently limiting commercial production. Synthetic and natural fibre spinning produces fibre dust (a few microns in size), due to abrasion and friction with various metallic parts of the different spinning machines. Although few studies have been carried out, inhalation of this fibre dust (even dust made from natural fibres) could be highly harmful to the staff working in these manufacturing facilities, potentially causing lung disease.

Effect on environment and biodiversity

As the textile industry uses a large volume of water, manufacturing facilities are usually located in close proximity to riverbanks. These rivers are also the prime receivers of the effluent produced, and carry pollutants to groundwater and also to marine ecosystems, contaminating them. The precise effects of these pollutants on soil and waterborne microorganisms, earthworms, aquatic animals, marine animals and other wildlife requires more extensive research. The appearance of microplastics in soil[49] and aquatic ecosystems[50] and humans[51] is well studied, driven by a surge in public interest in plastic pollution. Nonetheless, the effects of degraded and non-degraded dyes, non-degradable polymers, pesticides, antimicrobial agents, fluorocarbon finishes, etc., on the terrestrial and marine environment, conservation and biodiversity, their exposure and bioaccumulation, have not been considered. This is probably because of the rise in offshoring, whereby the majority of textile production moved from developed countries to low-to-middle income countries.

The most common life cycle assessment (LCA) methods also ignore the toxicity of these textile chemicals and auxiliaries. The European REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) regulation 1907/2006[52] restricts the use of many chemicals in textile substances and imported textiles. Substitution is preferred for certain substances with specific toxicological properties, and in the case of replacement with a low toxicity alternative, REACH authorisation is needed. REACH-restricted chemicals include various phthalates, azo dyes, mercury compounds, various dihalogen compounds, organostannic compounds, mercury compounds, cadmium, polybrominated biphenyls, nonylphenol ethoxylates, etc. The application of various biocides in textiles was restricted through regulation

47 Stark, A. (2011) Ionic liquids in the biorefinery: a critical assessment of their potential, *Energy & Environmental Science*, 4(1), pp.19–32.
48 Ryder, K., Ali, M.A., Carne, A., and Billakanti, J. (2017) The potential use of dairy by-products for the production of nonfood biomaterials, *Critical Reviews in Environmental Science and Technology*, 47(8), pp.621–642.
49 Guo, J.J., Huang, X.P., Xiang, L., Wang, Y.Z., Li, Y.W., Li, H., Cai, Q.Y., Mo, C.H., and Wong, M.H. (2020) Source, migration and toxicology of microplastics in soil, *Environment International*, 137, p.105263. Available at: https://doi.org/10.1016/j.envint.2019.105263
50 Ha, J., and Yeo, M.K. (2018) The environmental effects of microplastics on aquatic ecosystems, *Molecular & Cellular Toxicology*, 14, pp.353–359. Available at: https://doi.org/10.1007/s13273-018-0039-8
51 Prata, J.C., da Costa, J.P., Lopes, I., Duarte, A.C., and Rocha-Santos, T. (2020) Environmental exposure to microplastics: An overview on possible human health effects, *Science of the Total Environment*, 702, p.134455.
52 https://osha.europa.eu/en/legislation/directives/regulation-ec-no-1907-2006-of-the-european-parliament-and-of-the-council/ (Accessed: 10 October 2022).

(EU) 528/2012 concerning the market availability and usage of biocidal products.[53] The persistent organic pollutants (POP) Regulation (EC) 850/2004[54] restricts the use of various chemicals in textile materials, including pesticides, dioxins, dichlorodiphenyltrichloroethane (DDT), PFOA/PFOS, polycyclic aromatic hydrocarbons (PAH), and polybromodiphenyl ethers.

Hazardous chemicals (including triclosan, chlorinated compounds, endocrine disruptors, carcinogenic mordants, metal complex dyes, biocides, organohalogen-based fire retardants, etc.), are still used in textiles around the globe, which can endanger human health and cause considerable change in the ecology of the aquatic fauna and flora. To date, very few studies have been carried out in these areas. Stone et al. recently studied how global technological and societal processes shape the way we produce, use and dispose of textiles, and assessed their known and potential impacts on freshwater ecosystems.[55] They found that woollen textiles pose the most risk during the production phase, while PET textiles pose the most risk during the use and disposal phases. They also found that both 'natural' and synthetic textiles present substantial challenges for freshwater environments.

Very few studies have included the effect of textile dyes and chemicals on conservation and biodiversity. Environmental science analysis is needed to understand the effects and translate these to new methods of regulation/policy or alternative solutions for industry to implement, to reduce/mitigate the negative environmental effects of textile chemicals and dyes on our environment, ecosystems, conservation and biodiversity. Danger and risk need to be mitigated by technological advancements, with the replacement of the possible list of harmful compounds with sustainable ones, along with changes in regulations, consumer culture and use, as well as an emphasis on recycling/reuse.

Policy developments relating to Circular Fashion & Textiles

European Union policy is pursuing regulatory frameworks that support circular textiles. In March 2020, the European Commission launched the new Circular Economy Action Plan within the framework of the European Green Deal.[56] The action sets out new measures that focus on "strengthening industrial competitiveness and innovation in the sector, boosting the EU market for sustainable and circular textiles, including the market for textiles reuse, addressing fast fashion and driving new business models."

In 2025, it will become mandatory for all members of the EU to collect textiles waste separately from household waste. Extended producer responsibility (EPR) for textiles products will also be a priority — already operational in France,[57] it is also being developed in several other member countries, including Sweden.[58] In January 2021, the publication of the EU Strategy

53 https://asd-europe.org/guidance-for-asd-industries-the-eu-biocidal-products-regulation (Accessed: 10 October).
54 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2015.298.01.0001.01.ENG (Accessed: 10 October).
55 Stone, C., et al. (2020) Natural or synthetic — how global trends in textile usage threaten freshwater environments, *Science of the Total Environment*, 718, 134689.
56 European Commission (2020) Circular Economy Action Plan. Available at: https://ec.europa.eu/environment/pdf/circular-economy/new_circular_economy_action_plan.pdf
57 https://refashion.fr/pro/en/what-epr (Accessed: 10 October 2022).
58 https://www.ecotextile.com/2020121427132/materials-production-news/sweden-to-introduce-epr-for-clothing-and-textiles.html (Accessed: 10 October).

for Sustainable Textiles[59] reinforced this action and underlined the Commission's long-term commitment to EPR, textiles collections, the development and use of secondary materials through funding, and other indirect initiatives, for example, around circular business models and sustainable behaviour. This was further underscored in March 2022 with the adoption of the EU Strategy for Sustainable and Circular Textiles.[60]

In the UK, the Environmental Audit Committee (EAC) consulted on the topic of textiles and clothing production in 2018 and produced the Fixing Fashion: Clothing Consumption and Sustainability report in 2019.[61] The EAC launched a second consultation in 2020 and submitted evidence from this research to the UK government.[62] Although there was no direct action following the EAC recommendations, in March 2021 the Department for Environment, Food and Rural Affairs (DEFRA) stated that it would "seek to review and consult on" EPR for textiles by 2022.[63] It is hoped that the UK government will match European commitment to mandatory textiles collections, which will help to drive the feedstock preparation and scaling up of regenerative recycling technologies.

3.2 Key emerging themes

The textiles and fashion industry is understood to be one of the largest environmental polluters in the world. With the increase in global population during the 20th and 21st centuries, the demand for textiles and materials for apparel has multiplied and the balance of use from natural fibres to synthetics has shifted significantly (synthetics now represent approximately 62 percent of global fibre production).[64] The case for the shift to synthetics has been driven, rightly or wrongly, by imperatives to make textiles that are more durable, to meet increasing market demand, and to make textiles affordable for all.

This section covers the following themes, which are also mirrored in Section 4 (priority areas for research):

- **4.1 Supply Chain Impact Reduction**
- **4.2 Fibre and Chemical Loss**
- **4.3 Innovative Fibre and Recycling Technologies**
- **4.4 Circular Design and Business Models**
- **4.5 Interdisciplinary Research Methods**

59 European Commission (2021) EU Strategy for Sustainable Textiles. Available at: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12822-EU-strategy-for-sustainable-textiles_en
60 European Commission (2022) EU Strategy for Sustainable and Circular Textiles. Available at: https://ec.europa.eu/environment/strategy/textiles-strategy_en
61 Environmental Audit Committee (2019) Fixing Fashion: Clothing Consumption and Sustainability. Available at: https://publications.parliament.uk/pa/cm201719/cmselect/cmenvaud/1952/full-report.html
62 https://committees.parliament.uk/work/654/fixing-fashion-follow-up/publications/written-evidence/ (Accessed: 10 October).
63 DEFRA (2021) Waste Prevention Programme for England. Available at: https://consult.defra.gov.uk/waste-and-recycling/waste-prevention-programme-for-england-2021/supporting_documents/Waste%20Prevention%20Programme%20for%20England%20%20consultation%20document.pdf
64 https://www.commonobjective.co/article/synthetics-sustainable-synthetics-global-production (Accessed: 10 October).

→ 4.1 Supply Chain Impact Reduction

There is limited research into how to make textile production sustainable, or into the development of sustainable fibres, dyes and textile auxiliaries, compared to the currently used fossil fuel-based fibres, dyes and auxiliaries that have already been identified.

The reorientation of value chains towards sustainability and resilience is not solely defined by exploitation of natural capital.[65] For example, if a change in process results in a natural resource-intensive process which degrades natural capital through land-use change, leading to soil degradation or loss of biodiversity, this could not be considered a truly sustainable solution — even if there were an associated reduction in negative environmental impacts. The concept of renewable (or positive) natural capital should be incorporated within the development of new materials/processes to ensure that the proposed full value chain is both sustainable and resilient.

To help revive the UK textile processing industry, development of green alternative textile processing methods, e.g. sustainable zero-effluent and energy-efficient dyeing and finishing processes, and green multi-functional textiles development processes, is required. Recycled, recyclable and/or biodegradable alternatives to highly used poly(ethylene terephthalate) or PET-based polyester will need to be developed that match the performance of virgin PET-based polyester fibres.

The focus of this research theme is to replace harmful chemicals, dyes and textile auxiliaries used in the pre-treatment, colouration and finishing of textiles with environmentally friendly dyes and chemicals.

Scouring and bleaching processes

Traditionally, scouring and bleaching is used on natural raw materials such as cotton and linen, in order to soften and refine the fibres ready for use. This is carried out at the boil with a cocktail of alkali and nonylphenol ethoxylate-based detergent (an endocrine disruptor) that are environmentally harmful as they affect the aquatic ecosystem. Recent research emphasises reduction of water and energy usage and also replacing the alkali and detergents with enzymes and biosurfactants. Enzymatic bleaching, which replaces traditional chemical bleaching with enzymes,[66] has also been studied. Some of the enzymatic processes also enable combined scouring and bleaching,[67] but are rarely used in industry because of the high cost of enzymes compared to traditional bleaching chemicals.

Textile dyeing processes

Reactive and disperse classes of dyes are the most used textile dyes. Reactive dyes are the most problematic dye class, producing highly coloured effluent where up to 50 percent of the applied dyes are hydrolysed, do not

65 Dasgupta, P. (2021) The Economics of Biodiversity: The Dasgupta Review — Full Report, *HM Treasury*. Available at: https://www.gov.uk/government/publications/final-report-the-economics-of-biodiversity-the-dasgupta-review
66 Mojsov, K. (2019) Enzymatic desizing, bioscouring and enzymatic bleaching of cotton fabric with glucose oxidase, *Journal of the Textile Institute*, 110, pp.1032–1041.
67 Hebeish, A., et al. (2009), New development for combined bioscouring and bleaching of cotton-based fabrics, *Carbohydrate Polymers*, 78, pp.961–972.

bind to fibres and are therefore released into the effluent. The industrial pollution of water is a significant issue. The dyeing process consumes energy and water, with the majority of dyeing carried out using significant quantities of water at the boil. Research has been carried out to reduce the energy and water demands in dyeing and to reduce effluents.[68, 69]

More research in the following areas is required.

- **Closed-loop dyeing processes.**
- **Natural dyes derived from plants, fruits, and biomasses.**
- **Treatment of textile dye-house effluent (particularly in low-to-middle income countries).**
- **Development of biobased dye adsorbents suitable for industrial use.**
- **Alternatives for safe wrinkle-resistant, water-repellent, abrasion-resistant, antistatic, antibacterial and UV protective finishes.**

→ 4.2 Fibre and Chemical Loss

Substantial research has been carried out around the transportation and fate of synthetic microfibres, as well as microplastics released into the environment (water and air), their source, and their impact on the ecosystem and human health. Very little work has been carried out in the UK on microfibre release from textiles, and on how to mitigate microplastic fibre leaching from textiles.

More research in the following areas is required.

- **Differentiation between fibre types and sources of microfibre pollution.**
- **Relationship between fibre type (natural, synthetic or regenerated) and construction of fibre, yarn and fabric in fibre loss.**
- **Behaviour of fibres in different natural environments (marine, soil, rivers, etc).**
- **Compatibility of dyes and fibres for biodegradability and toxicity in natural environments.**
- **Mitigation of microfibre leaching from textiles by changing the design of yarn and fabric construction.**
- **Effects of microplastics and microfibres on wildlife and humans.**
- **Effects of bio-based nanofibres in air on health.**

→ 4.3 Innovative Fibre and Recycling Technologies

There is limited production of more sustainable natural fibres (such as wool, hemp and other bast fibres) and new sources of natural fibres need to be identified. PET-based polyester fibre has become the most popular new synthetic fibre for the manufacturing of textiles (more than 60 percent of textiles are made of polyester fibre). This is due to its advantages over other natural and synthetic fibres, such as low cost, excellent tensile

68 Khatri, A., Peerzada, M.H., Mohsin, M., and White, M. (2015) A review on developments in dyeing cotton fabrics with reactive dyes for reducing effluent pollution, *Journal of Cleaner Production*, 87, pp.50–57.
69 Hasanbeigi, A., and Price, L. (2015) A technical review of emerging technologies for energy and water efficiency and pollution reduction in the textile industry, *Journal of Cleaner Production*, 95, pp.30–44.

strength, easy dyability and colour-fastness properties, making its replacement challenging. Over the years biodegradable polymers have been developed, although none of them can match the cost and performance of polyester. Investment in novel biodegradable polyester substitutes that match the cost and performance of the PET-based polyester fibre may be beneficial. This requires consideration of the pitfalls of recent material innovation reliant on petroleum.

Bio-based fibres from waste
A new group of materials is emerging, with resource inputs based on various types of waste deriving from a broad spectrum of sources, including EOL textiles, and also from other industries (paper, food, agriculture, plastics, etc).

More research in the following areas is required.
- **Replacing synthetic polymers from virgin petrochemical sources.**
- **Profiling chemicals and wastes from emerging recycling technology processes.**
- **Scaling of reverse logistics to match scaling of recycling technology.**
- **Using biology and biotechnology processes to make fibres.**
- **Study of biodegradation of natural and regenerated fibres in real-world scenarios.**
- **Improvement in material performance of new fibres.**
- **Agritech challenges and opportunities for traditional fibres.**

→ 4.4 Circular Design and Business Models

Integrating environmental science research into the early stages of product development is an essential but under-developed practice. More work is needed to study how the particular characteristics of fashion and textile design research and LCA research can be integrated.

Several projects from UK-based design academics have brought together design and environmental science through projects focused on Circular Economy principles. The scientific theory development behind the design research process and the environmental science research process have both similarities and differences. The challenge here is to combine these processes into a single, interrelated approach.

More research in the following areas is required.
- **LCA standards for materials modelling — between worst/best case scenarios.**
- **The application of data to standard archetypes of apparel for comparison.**
- **Circular design strategies with EOL recovery sector.**
- **Circularity of use phases, specifically degradation through use and laundry.**

→ 4.5 Interdisciplinary Research Methods

There are emerging examples of Circular Fashion and Textiles industry-based research that respond to existing environmental science data.[70] Equally, there are examples of environmental science research being newly undertaken within a broader fashion and textiles context.[71] This research activity concedes the multiple environmental impacts of the fashion and textiles sector, suggesting environmental science has the potential to provide significant contributions across many of the prevailing complex challenges. These include reducing carbon and energy use; prevention of toxic emissions; prevention of fibre-shedding; and material recovery through both technical and biological means.

There is a paucity of UK research that seeks to tackle these challenges through complete cross-disciplinary integration at the outset. One negative impact of this lack of integration is the proliferation of contradictory evidence, which can create barriers to informed decision making across academic, scientific, policy and industrial contexts, especially regarding relatively recent (post-1900) materials science innovation.

It is imperative that the environmental and socio-economic science, design and humanities research communities and the FTT industry work together with the Environment Agency, DEFRA and other agencies, to understand current and future research challenges, informing the research, development and innovation necessary to circularise resources while minimising environmental impact.

The challenges and opportunities presented by cicularising the flow of materials resource requires a systematic approach, involving multiple disciplines and a coordinated programme of research across the entire system. The challenge requires input from a range of disciplines across the natural, social and economic sciences, as well as a wide range of stakeholders. Elements of research may need to consider life cycle assessment and material flows, technical, business and design innovations, principal transport pathways in the physical environment, socio-economic and health effects of resources. This includes, for example, microfibres in the environment, and the moderating effect of human behaviour and attitudes.

More research in the following areas is required.

- **Interdisciplinary approaches toward complex circular research outcomes.**
- **Institutions, industry bodies and third sector collaboration with government on investing in, promoting and implementing the upskilling of workers.**
- **Collaboration between brands (usually considered competitors).**

70 ASOS and Centre for Sustainable Fashion, UAL (2021) ASOS Circular Design Guidebook. Available at: https://asos-12954-s3.s3.eu-west-2.amazonaws.com/files/9516/3766/4620/asos-circular-design-guidebook.pdf
71 McQueen-Mason, S. (2020) *Bio-manufacturing textiles from waste.* Award ref. BB/T017023/1.

3.3 UK capabilities

Across the UK and EU, clothing accounts for a significant and growing proportion of household spending, yet lags behind in terms of addressing the environmental impact of apparel and textiles, with less than 1 percent of items fully recycled.[72] Loss of natural and synthetic fibres at different life cycle stages has contaminated all ecosystems. In a Circular Economy, these losses need to be designed out of the system, bringing significant benefits to the environment and human health. This entails generating world-leading science to support the EU and UK Circular Action Plans[73, 74] and Resources and Waste strategy,[75] and contribute towards the National Environment Research Council (NERC) vision of "leading our research community in working towards solutions for a productive, healthy and resilient environment."[76]

Regenerative recycling technologies in the UK (and abroad) are starting to scale up, and the significant interest in this field is justified. Nevertheless, there are challenges ahead, including better understanding of the environmental costs of such substitutions. WRAP has set out interim goals in its Textiles 2030 initiative, which aims to cut emissions from its signatories' operations by 50 percent, while "circular fashion transitions to business as usual"[77] by 2030.

UKRI funding allocations

In reviewing recent allocations of UKRI funding (2010-2022) in relevant areas of environmental science research pertaining to textiles and fashion, it was found that the largest proportion of funding was awarded to the sustainability assessment of textile products, circular design and circular bioeconomy, as well as the development of biobased plastics to replace non-degradable plastics.

Very little funding was provided to sustainable manufacturing of textiles, textile waste recycling, recovery of valuable components of textile waste streams, and mitigation of microfibre leaching from textile products during their washing and use. The majority of the funding was awarded by the Engineering and Physical Science Research Council (EPSRC), followed by the Arts and Humanities Research Council (AHRC).

Private and third-sector funding

There is also a significant level of private industry and third-sector funding of research to develop technology in the area of recycling technology, data interpretation and transparency in particular. Small and medium-sized enterprises in this field include **Worn Again Technologies**, **Resortecs**, **Renewcell**, **Infinited Fiber**, (recycling tech), **Made 2 Flow**, **MadeFrom**,

72 Environmental Audit Committee (2019) Fixing Fashion: Clothing Consumption and Sustainability. Available at: https://publications.parliament.uk/pa/cm201719/cmselect/cmenvaud/1952/report-summary.html
73 European Commission (2020) A New Circular Economy Action Plan.
74 DEFRA, DAERA, Welsh Government, and Scottish Government (2020) Circular Economy Package policy statement. Available at: https://www.gov.uk/government/publications/circular-economy-package-policy-statement/circular-economy-package-policy-statement
75 DEFRA and Environment Agency (2018) Resources and waste strategy for England. Available at: https://www.gov.uk/government/publications/resources-and-waste-strategy-for-england
76 https://www.ukri.org/councils/nerc/remit-programmes-and-priorities/our-research-portfolio-and-priorities/ (Accessed: 10 October).
77 https://wrap.org.uk/taking-action/textiles/initiatives/textiles-2030 (Accessed: 10 October 2022).

Segura, **Circular.Fashion** (transparency and data), **Ananas Anam**, **Modern Meadow** (materials development).

The top bio-based fibre companies, according to venture capital tracking, include bio-silk companies (**Commonwealth Scientific and Industrial Research Organisation**, **AMSilk**, **Kraig Biocraft**) and companies specialising in fibre innovations including cellulose, carbon monoxide, protein, algae and casein starting materials (**LanzaTech**, **Cellucomp** UK, **Chempolis**, **Algalife**).

WRAP

WRAP provides grants, loans and investments to help increase the use of recycled materials, growing recycling capacity or overcoming specific market failures by acting as a catalyst to encourage other funders to invest. Initiatives include the £1.4 million UK Circular Plastics Flagship Projects Competition; the £6.5 million Circular Economy Fund; and the £18 million Resource Action Fund (all programmes now closed for applications).[78]

The Circular Future Fund: The Million Pound Challenge

The John Lewis Partnership, in partnership with Hubbub, set up a £1 million fund to support trailblazing ideas and innovations that can accelerate the transition towards a more circular economy (January 2022).[79]

H&M Foundation: Global Change Award

The Global Change Award accelerates the transformation of fashion and is one of the biggest innovation challenges in the world for sustainable early-stage innovation, working in partnership with Accenture, KTH Royal Institute of Technology and the Mills Fabrica since 2016. A total of €1 million is shared between five innovations each year.[80]

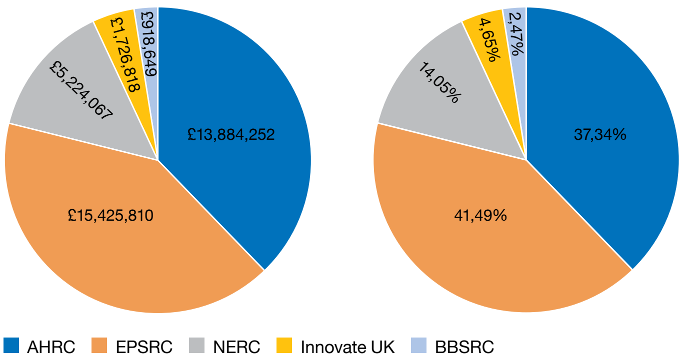

Fig. 1. Total funding in £ and percentage of research funding provided by the various UKRI Councils in environmental aspects of textile and fashion research.

Laudes Foundation (previously C&A Foundation)

An independent foundation and a part of the Brenninkmeijer family enterprise, Laudes Foundation aims to address the dual crises of climate breakdown and inequality by accelerating the transition to an inclusive and

78 https://wrap.org.uk/media-centre/press-releases/ps65m-fund-give-more-support-more-quickly-wider-range-organisations (Accessed: 11 October 2022).
79 https://www.circularfuturefund.co.uk/about (Accessed: 10 October 2022).
80 https://hmfoundation.com/gca/winners/ (Accessed: 10 October 2022).

regenerative economy. Laudes Foundation continues and advances the C&A Foundation's pioneering programmatic work in fashion, also building on the experiences of its flagship initiative Fashion for Good, and has extended this work to include the built environment and the financial sectors. The Foundation funds third-sector projects in line with its Theory of Change.

In 2020 & 2022 the following innovations were supported.
SALTYCO Healing the planet's most treasured lands and providing humans with cold-proof outerwear.
BIORESTORE A laundry solution that restores old and worn garments to mint condition.
COTTONACE An artificial intelligence solution that reduces pesticide use, increases yield and raises incomes for smallholder cotton farmers.
RE:LASTANE The first mild process making elastane and polyester blend fabrics recyclable.
RUBI Planet-positive viscose and lyocell made from carbon emissions.
GALY Growing high-quality cotton in a lab instead of on big farms, using less water and no land. The process emits far less greenhouse gas than traditional cotton. And it's fast, as much as 10 times faster than conventional cotton.
WEREWOOL Revolutionary fibres derived from nature itself. In the production process, the proteins found in organisms are built into the fabric on a DNA level to make biodegradable materials with the desired colour, stretch, moisture and water repellence. No need for further processing, which traditionally puts strain on the planet.
SEACHANGE TECHNOLOGIES Using a powerful jet engine to treat wastewater in the production stages in factories, by turning the toxic sludge into more manageable dry powder and extracting clean water to be released or reused.
TEXTILE GENESIS Using blockchain technology to track and verify the use of sustainable fibres all the way from fibre to garment. A digital fibercoin ensures transparency and reliability throughout the entire production line and beyond.
FAIRBRICS Instead of emitting carbon dioxide into the air, this innovation collects the gas, and activates and transforms it into sustainable polyester fabric that looks and feels like regular polyester.
ZER COLLECTION When making garments, a lot of fabric scraps are usually generated in the cutting process, which are simply thrown away. This innovation uses digital manufacturing to eliminate such waste and the 3D printed garment can easily be melted down into new fabrics and used again.

IKEA Foundation

IKEA is committed to tackling some of the root causes of inequality: poverty, the consequences of climate change, and lack of resources such as clean air, energy and fertile land, through grant making and advocacy. Research themes are prioritised according to impact and complexity with reference to UK research strengths and gaps.

4 Priority Areas for Research

Piñatex®, a vegan leather made out of pineapple leaf fibres by © Ananas Anam

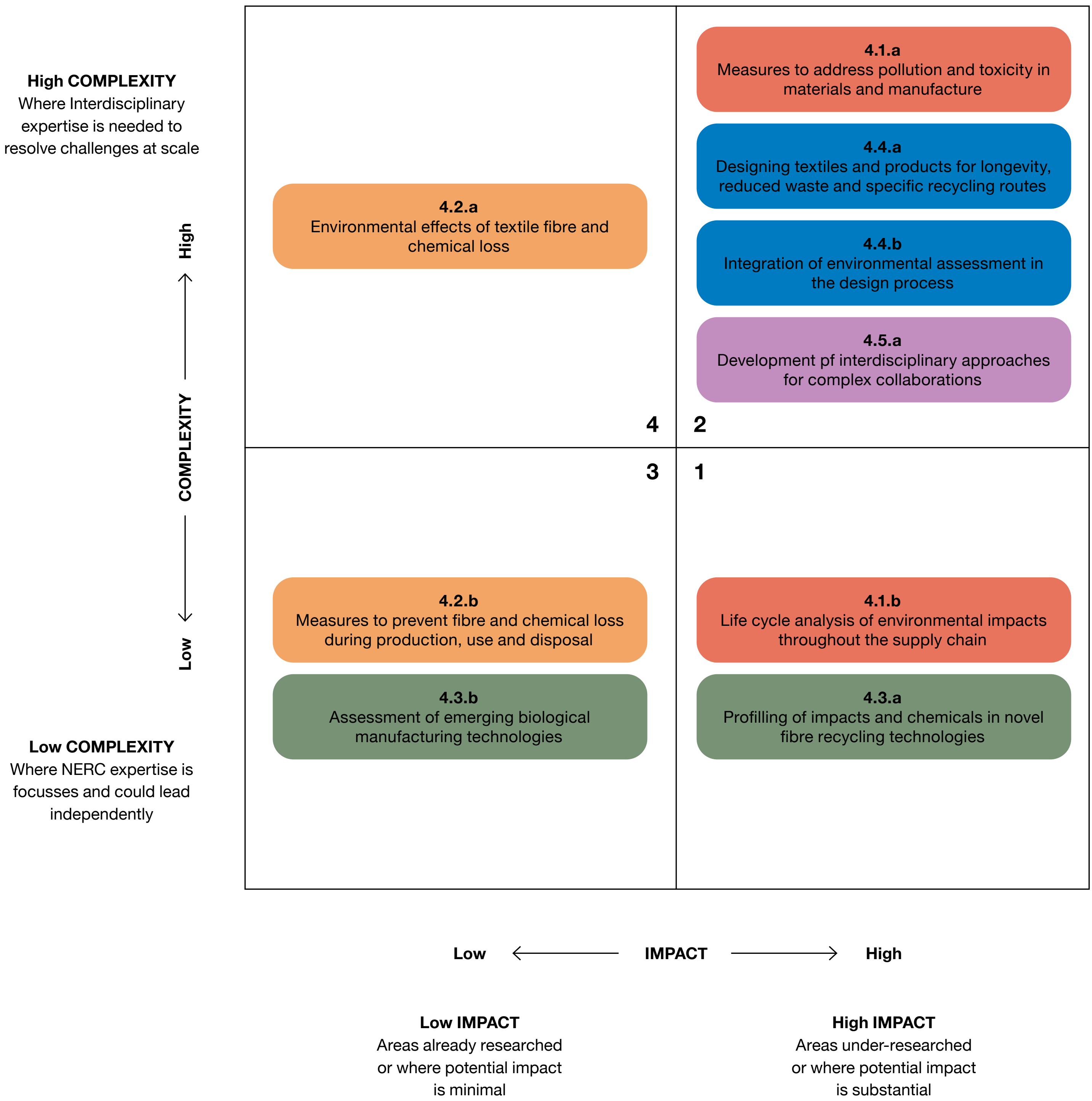

Fig. 2. Prioritisation of research themes according to impact potential and complexity of intervention required.

Research theme	Complexity (high/low)	Impact (high/low)	Rationale
4.1 Supply chain impact reduction Design alternative manufacturing and chemical processes to minimise environmental degradation and preserve natural resources			
4.1.a. Measures to address pollution and toxicity in materials and manufacture	high	high	Alternatives to the key textile chemicals related to pollution are urgently required. Focused research could be done in small multi-disciplinary groups. Requires collaboration with EPSRC, IUK and BBSRC.
4.1.b. Life cycle analysis of environmental impacts throughout the supply chain	low	high	Supply chain transparency and standardisation linking to env impacts is not established and would provide evidence base for substantial industry response. Requires large range of disciplines but is essential in addressing key industry challenges. Links to 4.4.a
4.2 Fibre behaviour and loss Building systematic understanding and mitigation of the primary chemical and fibre leakage points across the value chain for textile applications important to the UK economy			
4.2.a. Environmental effects of textile fibre and chemical loss	high	low	Already substantial research that provides basis for preventative action. Research is needed but provides impact in shorter time-frames if combined with mitigation practices (4.2.b).
4.2.b. Measures to prevent fibre and chemical loss during production, use and disposal	low	low	Research already developing in this area (combining a & b) and, while it needs complex multi-stakeholder engagement, it would be worthwhile.
4.3 Innovative fibre and recycling technologies (bio-based and synthetic) Ensuring that circular fibre technologies (both bio-based and synthetic) bring substantial environmental benefits across all impact categories and prevent regrettable substitutions			
4.3.a. Profiling of impacts and chemicals in novel fibre recycling technologies	low	high	Very little research currently linking F2F technology development and environmental science. NERC could lead on this potentially high impact research.

4.3.b. Assessment of emerging biological manufacturing technologies	low	low	Emergent and important body of research however timeframes to impact are behind those in 4.3.a. NERC could lead on focused research. UK agritech practices promoted through better environmental understanding. Suited to small scale but replicable capacity.
4.4 Circular design and business models Identifying promising design and technical interventions, business models and enabling conditions to address current issues in the fashion and textiles sector			
4.4.a. Integration of environmental assessment in the design process (env.-data driven design)	high	high	Burgeoning UK-led industry in this sector with high-level of investment. However DATA on which they rely is not universally agreed and requires support from env.science and associated expertise, regulation, standardisation etc.
4.4.b. Designing textiles and products for longevity, reduced waste and specific recycling routes	high	high	Incorporating insight from 4.4.a. Solutions must be matched to identified hot-spots in the env. DATA. Requires NERC-informed multi-disciplinary consortia with strong links to manufacturing industry.
4.5 Interdisciplinary research methods Fostering interdisciplinary approaches toward complex circular research outcomes and accelerated progress			
4.5.a. Development of interdisciplinary approaches for complex collaborations	high	high	All complex collaborative efforts outlined above in 4.1.a, 4.2.a, 4.4.a, 4.4.b require development of new interdisciplinary approaches and methodologies. These will need to be integrated into research proposals in order to ensure joined-up process.

Table 1. Rationale and ranking of themes for prioritisation according to impact potential and complexity

4.1 Supply chain impact reduction

Design alternative manufacturing and chemical processes to minimise environmental degradation and preserve natural resources

Industry needs and recommendations

In a Circular Economy, fashion and textile products are manufactured to circular design standards, moving away from a take-make-waste model. This incorporates decoupling production from the consumption of finite resources and reducing emissions from upstream operations. Examples include **decarbonising material production**, **material processing** and **garment manufacturing**, while also **minimising the production and manufacturing of waste.**[81, 82, 83]

This is achieved first and foremost by significantly reducing the need for virgin inputs through reuse, remaking and recycling; then by sourcing the remaining virgin inputs from renewable materials, using regenerative production practices.[84]

Manufacturers can collaborate with fibre-to-fibre recyclers to reprocess pre-consumer waste and drive demand for recycled fibres with retailers.[85] Additionally, **production, supply chain practices and technologies must ensure the effective use of resources**, for example by optimising the use of water, energy, chemicals, and materials.[86] In another realm (one that COP26 agreements[87] may instil), fashion and textile brands would ideally collaborate with manufacturers and logistics and digital innovators on the development and **adoption of technology that facilitates on-demand manufacturing and distribution**, meaning that only the exact quantity required is manufactured and there is no excess inventory that may end its life as waste.[88] While research would advance the field, it would have to be matched by regulation, evidence of feasibility, and a change in the pace, volume, and perceived material value imbued by the fashion, apparel and textile industry, as well as consumer change.

Technologies that may be adopted include traceability technology and predictive analytics that predict trends and consumer demand. Furthermore, brands and logistics providers can trial inventory models that enable small batches of new products and designs to be shipped, before quickly ramping up production if these prove popular, avoiding the production of excess inventory that would eventually become waste.[89]

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81 ASOS and Centre for Sustainable Fashion, UAL (2021) ASOS Circular Design Guidebook. Available at: https://asos-12954-s3.s3.eu-west-2.amazonaws.com/files/9516/3766/4620/asos-circular-design-guidebook.pdf
82 McKinsey & Company and Global Fashion Agenda (2020) Fashion on Climate. Available at: https://www.mckinsey.com/~/media/mckinsey/industries/retail/our insights/fashion on climate/fashion-on-climate-full-report.pdf
83 Ellen MacArthur Foundation (2020) Vision of a circular economy for fashion. Available at: https://emf.thirdlight.com/link/nbwff6ugh01m-y15u3p/@/preview/1?o
84 Ellen MacArthur Foundation (2020) Vision of a circular economy for fashion. Available at: https://emf.thirdlight.com/link/nbwff6ugh01m-y15u3p/@/preview/1?o
85 Wrap Textiles (2021) 2030 Roadmap. Available at: https://wrap.org.uk/sites/default/files/2021-04/Textiles%20 2030%20Circularity%20Roadmap.pdf
86 Ellen MacArthur Foundation (2020) Vision of a circular economy for fashion. Available at: https://emf.thirdlight.com/link/nbwff6ugh01m-y15u3p/@/preview/1?o
87 Available at: https://unfccc.int/sites/default/files/resource/cma2021_10_add1_adv.pdf (Accessed: 13 October 2022).
88 British Fashion Council/Institute of Positive Fashion (2021) The Circular Fashion Ecosystem: A Blueprint for the Future. Available at: https://instituteofpositivefashion.com/uploads/files/1/CFE/Circular_Fashion_Ecosytem_Report.pdf
89 British Fashion Council/Institute of Positive Fashion (2021) The Circular Fashion Ecosystem: A Blueprint for the Future. Available at: https://instituteofpositivefashion.com/uploads/files/1/CFE/Circular_Fashion_Ecosytem_Report.pdf

Additionally, **substances that are hazardous to health or the environment should be designed out**, allowing safe material circulation, and ensuring that no pollutants are released into the environment. This may be achieved by ensuring products and their materials are free from hazardous substances from the outset, and also by ensuring that the manufacture and subsequent use of products will not release hazardous substances into the environment.[90]

Manufacturers could **switch to safer or lower impact dyes**, for example natural dyes if these could be improved, while also ensuring that dyed material is colour-fast in ways that are not harmful (dope dying technology addresses this issue in synthetic fibres[91]). Emerging water-free laser technology can be used to alter and style fabrics such as denim, in place of water intensive stone washing used to date. Laser distressing technology can be used to enhance material properties and aesthetics, and this technology can also be applied to prepare materials for recycling. To make sure that no hazardous chemicals have been used during the recycling process, it is recommended that material producers should have a facility water programme in place to **manage effluent and reduce water use**, or a programme in place to achieve Zero Discharge of Harmful Chemicals (ZDHC).

Policy is required to ensure chemicals used within commercial products comply with the current ZDHC Manufacturing Restricted Substances List.[92] Additionally, brands can ensure that all the chemicals used in their products meet non-toxic certifications, such as those provided by OEKO-TEX ®.[93]

Brands are vulnerable to opaque parts of supply chain. EPR[94] policy changes pose financial and reputational risks to businesses if they are unable to track activity across the supply chain effectively. In order to tackle these challenges more effectively, large brands are putting significant resource into this area, with expanded teams covering all aspects of ethics and sustainability.

90 Ellen MacArthur Foundation (2020) Vision of a circular economy for fashion. Available at: https://emf.thirdlight.com/link/nbwff6ugh01m-y15u3p/@/preview/1?o
91 https://spindye.com/ (Accessed: 11 October 2022).
92 https://mrsl.roadmaptozero.com/ (Accessed: 11 October 2022)
93 ASOS and Centre for Sustainable Fashion, UAL (2021) ASOS Circular Design Guidebook. Available at: https://asos-12954-s3.s3.eu-west-2.amazonaws.com/files/9516/3766/4620/asos-circular-design-guidebook.pdf
94 Eunomia (2022) Driving a Circular Economy for Textiles through EPR. Available at: https://www.eunomia.co.uk/reports-tools/driving-a-circular-economy-for-textiles-through-epr/

4.1.a. Measures to address pollution and toxicity in materials and manufacture

The F&T sector understands that substances that are hazardous to health or the environment should be designed out, allowing safe material circulation, and ensuring that no pollutants are released into the environment.	
Industry pull / market failure Red = environmental science source	**Industry challenges include:** • functional surface treatments (anti-microbial, water/oil repellency) • non-hazardous colouration processes (C8-based fluorocarbons currently used contain carcinogenic perfluorooctanoic acid [PFOA] or perfluorooctanoic sulfonate [PFOS]) • alternative joining methods for textile materials (such as composites, laminates, coatings and stitching) • avoidance of chemical treatments that block methods of disassembly at end of life • considering toxicity in LCA • proven, sustainable green chemistry alternatives to current dyeing, finishing and joining processes in order to meet ZDHC standards. *"It's one thing to restrict the use of certain chemicals, but it's quite another to direct people to better chemistry and help them avoid making regrettable substitutions. That's when a chemical formulation we know to be hazardous is replaced with one which later turns out to also be harmful either alone or in combination with others."* ***"With fluoropolymers, there are still gaps in knowledge around exactly how they behave in the environment, and if we replace them with alternative chemicals, how do we really know it's not a regrettable substitution?"*** **This represents a market failure:** new green-certified chemistry needs to be developed to replace the most contentious chemicals used in FTT sectors.
Opportunity	**This represents a pre-competitive opportunity:** industry achieving sustainability goals; carbon targets; consumer relationship building; and de-risking business interests by meeting anticipated regulatory changes.
Research questions Red = research questions with a leading environmental science component	• **How can common measures of toxicity be established within LCA practices?** • **How can green chemistry achieve low environmental impact textile dyes with colourfastness or other functional finishes?** • What methods of textile joining can be used to minimise chemicals use during manufacturing processes and ensure recyclability? • How can functionality be designed into fabrics with safer chemical or mechanical process alternatives?

Environmental science contribution	**Addressing research gaps will require environmental expertise in:** • health and ecotoxicology — particularly green chemistry • water quality — particularly modelling of processes that control water quality and setting safe levels • environmental informatics — particularly LCA standardisation • (medical) toxicology — particularly identifying effluents damaging to human health.
Interventions	These areas of research would usually sit within EPSRC funding remits. If this type of research were led by NERC interests, it could ensure that future science and innovation is driven with the imperative to mitigate environmental impact from the outset. Research funding calls would benefit from interdisciplinary grants, using a transdisciplinary consortia approach, to convene industry, environmental science, engineering, design and anthropology. Innovate UK initiatives led by industry, and aligned to NERC remit may be relevant, once higher TRLs are achieved.

4.1.b. Life cycle analysis of environmental impacts throughout the supply chain

There is industry demand for environmental data from upstream operations, such as material production, material processing and garment manufacturing, in order to design out impacts within the supply chain.	
Industry pull / market failure **Red = environmental science source**	**Industry challenges include:** • fashion brands seeking to understand environmental data from across the supply chain • technology start-ups finding novel ways to present data effectively • transparency and standardisation for data integration across complex supply chain tiers • agreed approaches to understanding carbon impacts and their interconnectivity across the supply chain • quantifying and modelling impacts with support from disciplines engaged in fibre, manufacture and garment design and production • robust tracing methods that work at fibre level (product labels are often removed during use or the sorting process) • data collection as part of the manufacturing process • revised allocation of system boundaries for LCA studies that attribute effects outside of the system (e.g. in the emergent use of agricultural wastes or recycled fibres) • methods to validate research through academic partnerships. *"The environment team (55 staff) is focused on things like biodiversity and food waste, the circularity team on looking at circular design and business models (take-back schemes, buyback, repair, rental and*

	corresponding legislation), another team looks specifically at climate targets and science-based targets, reducing our carbon emissions, and another at raw materials (including agriculture around materials like cotton, hemp, timber, palm oil) and lastly a separate human rights team looks at auditing and ethical trade." *"A breakthrough blend of machine learning, systems thinking and decision intelligence will define a new era of business and equip business to make better products."* *"We're focused on reducing our carbon water and waste emissions in line with WRAP's Textiles 2030 commitment…but we do need external expertise and research to evaluate and embed the work that we've done."* *"The fashion industry was the first sector to be investigated for 'misleading green claims' by the Competition and Markets Authority (CMA), according to the Green Claims Code, with a view to carrying out a full review of misleading green claims in early 2022."* ***"The environmental impact of [fibres] is not limited to their end-of-life degradation. Impacts arise across their whole life cycle. New processes are needed to manufacture, process and recycle [fibres] that adhere to rigorous sustainability metrics."'*** ***"There are some processes that have been in industry for so long that their impact on the supply chain is probably very low. Any emerging technology impact is higher [at the start] than it's going to be in 10 years' time."*** **This represents a market failure:** i.e. the lack of incentive for individual businesses to define data integration standards.
Opportunity	**This represents a pre-competitive opportunity:** brands are ready to pilot and roll out new models for production and supply chain design. This could accelerate progress towards carbon targets and enhance profitibility within UK supply chains. All industry partners across supply chains would benefit.
Research questions Red = research questions with a leading environmental science component	• **How can impact assessment be standardised in order to usefully compare carbon impact reduction across distributed supply chains?** • **How can artificial intelligence and detailed modelling of supply chains identify the most promising interventions for carbon reduction?** • **How can environmental impact data be effectively collected and analysed in real time during production of material and garment products?** • **Can post-industrial/production impacts be quantified considering financial risks of changing regulation and polluter-pays regulation?**

	• **How can multi-factor environmental impact analysis of production methods be achieved as they are scaled through TRL stages?** • Could inclusion of improved accessible social impact data be used to steer chosen materials/designs/manufacturing methods? • How can fibre-based materials be accurately tracked through the supply chain as they are transformed (from fibres to materials, fabrics, products and waste streams)? • How can scaling activities be developed in line with net zero targets and consider the transition to renewable energy within the UK?
Environmental science contribution	**Addressing research gaps will require environmental expertise in:** • environmental informatics — particularly LCA standardisation and LCA methodologies including social factors (Env. S-LCA) • (medical) toxicology — particularly identifying effluents damaging to human health.
Interventions	An R&D intervention/open-innovation call supporting an academic and industry alliance to develop open-source tools to generate a standardised view of impact (ref. 3.4. Circular design and business models). A Network Plus mechanism to support collaboration across industry and higher education institutions (HEIs) to determine longer-term future research challenges — rapid transfer and adoption, with industry-led pilot projects built into an overarching programme of research. Studies co-developed through material science, artificial intelligence and environmental science, assessed by LCA methodologies and partners. The inclusion of local authorities, business, national (funded), and global (partner) HEIs to ensure reach.

4.2 Fibre and chemical loss

Building systematic understanding and mitigation of the primary chemical and fibre leakage points across the value chain for textile applications important to the UK economy

Industry needs and recommendations

The environmental presence of microfibres is expected to increase as global textile consumption increases; annual **global fibre production of textiles is estimated to increase by about 33 percent to 146 million metric tonnes by 2030** (from 109 million metric tonnes in 2020).[95]

Better **understanding of how fibres behave in the environment** is imperative (i.e. bio-degradation of major fibre groups in terrestrial and marine environment and release of harmful pollutants). Research is needed into what they are and where this is happening, what the impact is, and assessing how the most harmful leakages can be mitigated.

Moving away from a take-make-waste model, **minimising the production and manufacturing of waste** must also include the release of microfibres. These can potentially cause harm and pollute the environment and therefore should be prevented either through design or collection.[96] All fashion and textile businesses have a responsibility to adopt and adhere to aligned cross-industry guidelines, to **minimise the impact from fibre fragmentation.**[97]

Interventions can be made to **reduce the number of fibre fragments finding their way into water systems**, including changes in the type of yarn, textile, and garment design/construction. Modification of laundering processes, for example, captures microfibres via filters in washing machines, and better filters also capture fibres in wastewater treatment. It is important that the government facilitates **collaboration between fashion retailers, water companies and washing machine manufacturers**, and takes a lead on solving the problem of microfibre pollution. Ultimate responsibility for stopping this pollution, however, must lie with the companies making the products that are shedding the fibres. Additionally, urgent research requires to be carried out into the occupational health risks of working in environments where fibre fragments are released.[98]

There is a tendency within the industry to focus mainly on synthetic fibre fragmentation, but **equal priority must be placed on synthetic and natural fibres**, which both shed during textile manufacturing and do not always degrade once in the environment. Fashion, apparel and textile manufacturing facilities which discharge treated wastewater directly into the environment, or discharge indirectly through a centralised treatment

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95 Textile Exchange (2020) Material Change Insights Report 2020. Available at: https://textileexchange.org/wp-content/uploads/2021/05/Material-Change-Insights-2020.pdf

96 Ellen MacArthur Foundation (2020) Vision of a circular economy for fashion. Available at: https://emf.thirdlight.com/link/nbwff6ugh01m-y15u3p/@/preview/1?o

97 The Microfibre Consortium (2022) TMC's position on the control of fibre fragmentation, within textile manufacturing wastewater. Available at: https://static1.squarespace.com/static/5aaba1998f513028aeec-604c/t/6201407a1ff01f0cbb15b908/1644249210577/TMC_Manufacturing_TMC+Position+Statement_Final.pdf

98 Environmental Audit Committee (2019) Fixing Fashion: Clothing Consumption and Sustainability. Available at: https://publications.parliament.uk/pa/cm201719/cmselect/cmenvaud/1952/1952.pdf

plant, must install **an aligned and formalised approach to the on-site filtration of fibre fragmentation from wastewater** generated during textile manufacturing. Facilities with zero liquid discharge must manage sludge in a manner that prevents the release of fibres into the environment. Furthermore, it is recommended that centralised effluent treatment plants also consider these methods and approaches, to mitigate release of fibres generated primarily from domestic sources.[99]

Biodegradability should not be endorsed as a 'solution' to fibre fragmentation from textiles. However, once the following steps have been undertaken, there is a possibility biodegradability may be a viable approach for removing fragmented fibres from the environment. For biodegradability to be considered, it has been recommended that a methodology for assessing fibre fragmentation aligns across the industry. **Biodegradation methods should also come as close as possible to representing real-life situations**, as this is when the advantages of biodegradation are realised; for example, low temperatures, limited light or UV, and limited oxygen.

There must be **cross-industry alignment on the pathways and intended receiving environment(s) for testing**, e.g. fresh water, marine water, soil, anaerobic and aerobic conditions, etc. There must be value of testing versus company resources. Which test methods can provide cost-effective results and an appropriate approach for correlation and modelling must be identified: lab testing is quicker but field testing is done in a real-life environment. This should ideally be reviewed in the wider sustainability context, to ensure it doesn't raise any larger issues. Furthermore, it is vital that toxicological work is carried out to determine the effect of fibres as carriers of chemicals into the environment.[100]

Industry response to this relatively new area of study is hampered by inaccurate or undetailed press coverage that conflates microfibres, microplastics and plastic litter in the environment. Key initiatives from Industry Acting on Microfibres[101] and the Ocean Conservancy[102, 103] include The Microfibre 2030 Commitment,[104] which forms an aligned agenda for the sector with **understanding (see 4.2.a)** and **mitigation (see 4.2.b)** as two clear goals.

99 The Microfibre Consortium (2022) TMC's position on the control of fibre fragmentation, within textile manufacturing wastewater. Available at: https://static1.squarespace.com/static/5aaba1998f513028aeec604c/t/6201407a1ff01f0cbb15b908/1644249210577/TMC_Manufacturing_TMC+Position+Statement_Final.pdf
100 The Microfibre Consortium (2022) TMC's position on biodegradability in the context of fibre fragmentation. Available at: https://static1.squarespace.com/static/5aaba1998f513028aeec604c/t/61e002c53fed1c54b171cd85/1642070725693/TMC_Biodegradability_TMC+Position+Statement_FINAL+.pdf
101 https://iamicrofibres.com/ (Accessed: 11 October 2022).
102 https://oceanconservancy.org/ (Accessed: 11 October 2022).
103 https://usplasticspact.org/roadmap/ (Accessed: 11 October 2022).
104 https://www.microfibreconsortium.com/roadmap (Accessed: 11 October 2022).

4.2.a. Environmental effects of textile fibre & chemical loss

Understanding fibre and textile chemical behaviour in the environment, including bio-degradation of major fibre groups in terrestrial and marine environment and release of harmful pollutants.

Industry pull / market failure Orange = environmental science source	**Industry challenges include:** • systematic study of the main chemical and fibre leakage points across textile and apparel supply chain • clearer regulation of microfibre release • value, behaviours and effects of lost resources through fibre fragmentation (and associated chemical leakage) • understanding effects on both human health and wildlife ecology • evidence of impacts on biodiversity through both synthetic and natural fibres in the environment • understanding of health risks of airborne fibre fragments in the atmosphere • Further developments in research and testing methodologies for biodegradability. ***"We must understand whether there is any toxicity from [fibres] and their degradation products, at all size scales of waste fragments. This will require detailed knowledge of the biological pathways involved in the chemical and particle toxicity of microplastics. It should also consider both direct and indirect ecological effects, such as a reduction in food availability for other species, transportation of pollutants, and formation of biofilms."*** *"We're not only talking about microfibres from plastic — we need to understand the full fibres picture. We have the support of the microfibre consortium and are working with them on a road map for microfibres as well as developing a tool to measure microfibre shredding with HKRITA (a research institute in Hong Kong)."* **This represents a market failure:** due to the expansive and unconnected nature of cause and effect this is not something industry could (or would have any incentive to) solve alone. UKRI has an important role to play in further understanding the cause and effects of fibres and textile chemicals in the environment.
Opportunity	**This represents a pre-competitive opportunity:** There is clear financial benefit to industry of maximising efforts to minimise fibre shedding, as outlined in the latest report from the Sustainable Investment Institute, as well as regulatory and consumer pressure.
Research questions Orange = research questions with a leading environmental science	• **Which hitherto unknown/unmeasured run-offs during production and finishing processes might be harmful to marine, terrestrial and atmospheric environments?** • **What are the detailed profiles of fibres (both synthetic, semi-synthetic and natural) found in ocean studies, and which**

	dyeing and finishing chemicals are present? • Can sources of fibre pollution be identified through integration of fibre identification technologies (e.g. those based on forensic science)? • To what extent does manufacture and pre-consumer activity contribute to microfibre loss? • What is the split between synthetics, semi-synthetics and natural fibres in industrial fibre loss? • What are the potential health risks of airborne fibre fragments in the atmosphere and can risks be differentiated by fibre type? • How is the biodegradability of fibres affected in different contexts — soil, landfill, marine or industrial composting environments?
Environmental science contribution	**Addressing research gaps will require environmental expertise in:** • water quality — particularly modelling of processes that control water quality and setting safe levels • (medical) toxicology — particularly identifying effluents damaging to human health • health and ecotoxicology — particularly green chemistry • marine environment sciences — including ecohydrology and biogeochemistry, environmental nanosciences
Interventions	Weight of research in this area sits with environmental and material sciences but also requires inputs from toxicology and pollution, with fibre profiling from textile/material science and technology. Co-production of knowledge would allow for a more comprehensive understanding of both problem and solution in this area (industry and scientists have different solutions to the same problem).

4.2.b. Measures to prevent fibre and chemical loss during production, use and disposal

Interdisciplinary research to quantify effectiveness of fibre and chemical loss mitigation (and valorisation) tactics during all stages of the product cycle and fibre types/textile construction.	
Industry pull / market failure Orange = environmental science source	**Industry challenges include:** • confirming best practice in mitigation through design and manufacture (including changes in types of yarn and garment design/construction) • identifying opportunities for closed-loop processes and win-win solutions for chemical recovery • prevention of fibre fragmentation via modification of laundering processes (e.g. capture via washing machine filters, and/or filters to capture fibres in wastewater treatment).

	"It's about prevention — to understand how we can mitigate fibre loss in the first place. How can we construct the fabrics in such a way that they shed less? It's also in the garment manufacturing stage." ***"The recent UN Environment Assembly is not just focusing on marine pollution, but also looking at the how it links to manufacturing and the whole of the supply chain so the focus is on intelligent resource use, looking at how we can reuse resources from misuse or pollution. Wastewater pollutants, when you take them out of the context of the waste or the water, can also be a product."*** **This represents a market failure:** calls for regulation and policy change in this area will undoubtedly increase pressure on brands to act, but scientifically rigorous research is required to validate any mitigation actions that industry might consider.
Opportunity	**This represents a pre-competitive opportunity:** If mitigation techniques both in manufacturing as well as user settings (laundry) can be proved, there is potential for industry and the public to adress this relatively new but substantial issue. New products and materials to filter out fibres before they reach the environment present an opportunity for commercial development.
Research questions **Orange = research questions with a leading environmental science**	• Which measures to prevent fibre fragmentation through design and manufacturing are most effective? • What benefits could be found in replacing traditional cutting and bonding processes with thermal bonding and cutting technologies (e.g. laser-based processes)? • Which textile processes have potential for the creation of useful co-solvents for valorisation and mimimising waste outputs? • **Which valuable resource components (dyes, salt, minerals, etc.) currently wasted through textile processing (e.g. dyeing and finishing) could be valorised?** • **Where are there opportunities for industrial symbiosis through improved filtration to capture fibres in wastewater treatment or effluent valorisation through bioprocesses (fermentation)?**
Environmental science contribution	**Addressing research gaps will require environmental expertise in:** • water quality — particularly modelling of processes that control water quality and setting safe levels • health and ecotoxicology — particularly green chemistry • environmental informatics — including technology for environmental applications.

Interventions	Research should ideally involve collaboration between fashion retailers, water companies and washing machine manufacturers, in addition to environmental science. Research initiatives that close knowledge and data gaps regarding the occurrence of microfibres in the environment (including environmental and human health risks posed), as well as developing and comparing mitigation solutions, would be beneficial.

4.3 Innovative fibre and recycling technologies (bio-based/synthetic)

Ensuring that circular fibre technologies (for both bio-based and synthetic materials) bring substantial environmental benefits across all impact categories, and prevent regrettable fibre substitutions.

Industry needs and recommendations

Fibres from both **optimised circular synthetic and new bio-based sources** have potential to fulfil our material needs in more sustainable ways, by replacing more impactful materials. New sources for cellulosic fibres will need to be identified, as cotton production has high environmental impacts. Textile fibre production is now turning from geology to biology, including terrestrial and marine algae. Environmental science has a valuable role to play in the **development of recycling and regeneration technologies**, by understanding their likely impacts. **Early intervention in the fibre development process** will help mitigate any potential environmental or social harm before it reaches full scale.

A huge number of 'circular' fibre technologies are beginning to enter the commercial market. Assessing the environmental impact, and indeed the efficacy of circular fibres is vital for businesses, consumers and policymakers, in order to decide on effective sustainable solutions. **The industry should not make a kneejerk switch from synthetic to natural fibres** in response to the problem of microfibre pollution, as, given current consumption rates, this could result in pressures on land and water use. Encouraging a move from conventional materials to organic or recycled could help to reduce the impact of this industry.[105]

The mechanical recycling industry is witnessing renewed innovation, having remained largely unchanged for the past 200 years.[106, 107] While chemical recycling arguably presents opportunities for larger-scale recovery operations, there are advantages to mechanical processes that are available today and that work with lower energy and chemical inputs.

To make recycling viable, the scale of reverse logistics and infrastructure (i.e. collection, sorting and preparation technologies) needs to provide a reliable and suitable supply of feedstock and material inputs (volume and quality factors).

The UK requires brands, retailers and consumers to **drive the demand for recycled and renewable fibres**. Brands will need to lead multi-stakeholder initiatives to map out requirements, to ensure designs are suitable for reprocessing and also that recycled inputs are suitable for design and creation, as regards choice, speed and price. It is also important that **brands change the internal negative perception of recycled content** through education and training. Additionally, brands should collaborate with retailers to engage with consumers to promote the benefits and use of recycled content, while also working with academia to convey these

105 Environmental Audit Committee (2019) Fixing Fashion: Clothing Consumption and Sustainability. Available at: https://publications.parliament.uk/pa/cm201719/cmselect/cmenvaud/1952/1952.pdf
106 https://www.ukft.org/camira-iinouiio/ (Accessed: 11 October 2022).
107 https://www.projectplanb.co.uk/ (Accessed: 11 October 2022).

benefits to fashion and textiles students, and independent designers[108].

For these initiatives to be successful, government needs to **develop feed-stock standards** that become part of an Extended Producer Responsibility scheme for the textiles recycling industry. Other necessary initiatives include **standardised labelling**, to ensure accurate information for textile reprocessors, manufacturers, and consumers; **standard definitions and processes for recycling**; and clearer **standardised definitions of waste.**[109]
There is potential to **reinvigorate the use of traditional local fibre** use (animal and plant based) with agri-tech innovation[110] and developments in processing and finishing of **fibres such as British wool and linen**. With bio-based materials embedded in agriculture, impacts on land use, e.g. for food production, need to be considered against any perceived environmental advantages.

Biological manufacturing is an emerging technology with potential for development, although in a timeframe beyond that of the impending environmental crisis. This sector also requires careful scrutiny to ensure it is genuinly fit for purpose, and not merely meeting innovation and commercial objectives that may in fact be environmentally damaging. The field includes biosynthetic, bioassembled and biofabricated materials, and production techniques from traditional to synthetic biology, using living organisms (microbes, rather than plants or animals) as factories.[111] The range of approaches here is broad, e.g. new 'leathers' such as Piñatex, made using agricultural biproducts.

4.3.a. Profiling of impacts and chemicals in novel fibre recycling technologies

Profiling of chemicals and wastes of emerging chemical and mechanical fibre recycling technologies for the main fibre groups (polyester, cotton and regenerated cellulose).	
Industry pull / market failure Green = environmental science source	**Industry challenges include:** • replacing synthetic polymers from virgin petrochemical sources • scaling up chemical recycling processes for synthetics and blended fibre inputs (several UK companies are currently at pilot scale, with commercialisation planned before 2025) • understanding chemicals and wastes from emerging recycling technology processes • evaluation of potential for valorisation of chemicals otherwise considered pollutants

108 British Fashion Council/Institute of Positive Fashion (2021) The Circular Fashion Ecosystem: A Blueprint for the Future. Available at: https://instituteofpositivefashion.com/uploads/files/1/CFE/Circular_Fashion_Ecosytem_Report.pdf
109 British Fashion Council/Institute of Positive Fashion (2021) The Circular Fashion Ecosystem: A Blueprint for the Future. Available at: https://instituteofpositivefashion.com/uploads/files/1/CFE/Circular_Fashion_Ecosytem_Report.pdf
110 UKRI is investing in agri-tech as a key strategic area of research. https://www.agritechcentres.com/agri-epi-centre (Accessed: 11 October 2022).
111 Biofabricate and Fashion For Good (2021) Understanding "Bio" Material Innovations: a primer for the fashion industry. Available at: https://app.box.com/s/amjq9anszv8hvwdexoxg6wubes4aaxqa

	• scaling of reverse logistics to match scaling of recycling tech and removing regulatory blocks to waste management • encouraging a move from conventional to recycled materials • developing policy around feedstock standards, and standard definitions and processes for recycling and waste streams, including local authority collection systems • developing technological systems for optimised recirculation through collectors working with recommerce platform providers, brands and digital innovators. ***"90 percent of petrochemicals are used for fuel and only 10 percent for materials…and 80 percent of that 10 percent is plastics. Without the subsidy from the fuel, the mining of petrochemicals will not be economically viable, so finding alternatives to synthetic polymers (which include both recycled and alternative polymers) pretty quick is essential (because we've already decided to do that by 2050)."*** ***"Linings and all the other textile components (starch, finishes, adhesives, etc.) are not included on the [garment] tag, so, for example, there could be hidden nylon in a 100 percent cotton garment…I think that clearer tagging information is an absolute must for making sorting for recycling feasible."*** ***"There's a big problem here with waste — from the EU perspective, once something has been characterised as a waste it has to be dealt with by a waste management company, which can then create a block to recovery."*** *"Switching out virgin materials for recycled is definitely the biggest win as long as they are cost-neutral compared to virgin materials. The technology is there, but if you compare like-for-like it's more expensive. But I'm thinking about the legislation that comes in, the taxes, the kind of value that you could wrap into those changes that maybe aren't traditionally considered…one exciting part of this kind of circularity work is that you can uncover new areas of value that you you didn't have before, particularly in waste-as-resource initiatives, looking at the economics of some of our supply chains and seeing if there are more opportunities."* *"The word recycling is used as a single activity, when there are almost as many different ways of recycling material as there are of making it in the first place. So we want to have more data to understand the impact of all the different recycling technologies, and also where the waste comes from."*
Opportunity	**This represents a pre-competitive opportunity:** if successfully commercialised and taken up by industry, F2F recycling has the potential to revolutionise material use in the textile and apparel sector.

	This will have far-reaching consequences regarding the stability of future resources and the associated economic advantages and resilience of the industry. As around 70 percent of global fibre use is suitable for chemical recycling, this approach has the largest potential for impact of all solutions currently being explored, in the shortest time-frame.
Research questions Green = research questions with a leading environmental science component	• How can feedstock standards and definitions be incorporated into collection and sorting processes for recycling and waste? • How can definitions of waste be standardised across geographical and geopolitical boundaries to avoid system barriers for reuse and recycling? • **What is the effluent concentration (chemical and biological content of wastewater) in textile and fashion industry production processes and how can safe disposal into natural environments be assured?** • **What is the environmental impact of chemicals used in emergent chemical recovery processes (e.g. ionic liquids used in dissolution processes) and how can they be kept safely within a closed system?** • **What are the economic and environmental benefits of local and distributed chemical recycling hubs in addition to onshoring of production in the UK?** • **What are the environmental and economic benefits of a move from conventional to mechanically recycled textile materials with production in the UK?** • **How can fibre identification technologies (also useful in the microfibres space, Sections 4.2 and 4.3.b) be developed and used to quantify fibre flow in a UK F&T system?**
Environmental science contribution	**Addressing research gaps will require environmental expertise in:** • environmental survey and modelling tools • water quality — particularly modelling of processes that control water quality and setting safe levels • (medical) toxicology — particularly identifying effluents damaging to human health • health and ecotoxicology — particularly green chemistry
Interventions	Assessment of ecosystem shift towards regenerative fibre recycling through dedicated research is required. A collaborative initiative mapping anticipated future flows of materials, stakeholders and the economic case for an ecosystem shift towards regenerative recycling is necessary.

4.3.b. Assessment of emerging biological manufacturing technologies

There is growing interest and UK research into textile fibres from bio-based wastes and biorefinery production; like chemical recycling of synthetics, this area is emerging and requires further scrutiny.

Industry pull / market failure Green = environmental science source	**Industry challenges include:** • using biology and biotechnology processes to make fibres through the transformation of carbohydrates into proteins (replacing some agriculture or oil-based chemistry) • the potential for genetically engineered (meta) materials that go beyond what nature can currently provide — and related regulation • comprehensive study of biodegradation of natural and regenerated fibres in real-word scenarios to inform any industrial composting activity (there are numerous barriers to its deployment in current systems) • improving material labelling to reflect differentiation across basic fibre types; understanding of biological wastes including concentrations and combinations • further improvement in material performance of new fibres (e.g. durability, response to heat and water during production and use, etc.) is needed before conventional cotton and synthetics can be replaced at scale • understanding of agritech challenges and opportunities for traditional fibres based on local regenerative farming and processing • innovation to improve quality of vegan leathers (there is strong nonwoven and leather expertise in the UK) • development of food waste/by-product initiatives which largely produce regenerated cellulose outputs. ***“Even with 100 percent biological fibres there needs to be measures for chemical balances, to make sure if you’re releasing anything back, even though not apparently toxic, it’s at the right concentration.”*** *“With a lot of these [new] bio-based materials, we still don’t know enough about them. So even though a lot of people are excited by them, we definitely need more [verified] data, especially if we want to scale up using those materials. We need to understand more about what the impacts are…we know that the legislation around greenwashing will come into play quite soon, so we need to be really careful about when we’re calling something out as being a more sustainable material that we actually have the evidence to back that up. So we’re definitely interested in those new materials, but we’re also keeping an eye out for LCA data.”* *“It’s about data availability…There needs to be a common database for [sustainable] textiles. That would be something that we really need to strive towards, but even with the upcoming EU PEF legislation, it’s unclear about the data part.”*

	"I think that the most important thing, rather than having a biotech or compostable product, is to work on on your supply chain and reduce the impact there, and recycle, because when you degrade materials then you need to create new. So you need to make sure that impact is very low if your aim is to biodegrade. Of course everyone wants the most green product that they can have, but if it doesn't perform as required they will continue using their old material."
Opportunity	**This represents a pre-competitive opportunity:** a very large number of UK-based technology and materials companies are unable to thrive without endorsed LCA data to support their growth in the market. All industry partners across supply chains would benefit. Genetically modified meta materials, currently at very early stages of development, show promise.
Research questions Green = research questions with a leading environmental science component	• **Which key fibre groups present in post-consumer textile waste would be suitable for industrial composting in controlled conditions?** • **What might the environmental impacts be of bio-based but monoculture fibres or novel bio-based feedstocks (e.g. algae)?** • **What are the economic and environmental benefits of alternative production methods, e.g. local, distributed manufacturing that could be achieved in the UK with bio-based materials?** • **What levels of sugars and other biological fibre production outputs are safe to release into the environment?** • **How can we understand the performance of novel fibres against a range of fibre applications and compared to established fibre groups (cotton and polyester) as part of an environmental impacts study?** • **How can we understand both physical and emotional durability relating to optimised material use and associated environmental costs?** • **Can we exemplify benefits of onshore practices (agri-tech, local production) on biodiversity, pollution and land use? (Relating to UK wool, leather, linen and hemp production.)** • How might users respond to novel biological or genetically engineered materials in the marketplace? • How can re-processors access information on material composition (fibres, finishes, embellishments) including those added during use (starch, patches, adhesives) without relying on labels?

Environmental science contribution	**Addressing research gaps will require environmental expertise in:** • LCA methodologies • environmental survey and modelling tools • water quality — particularly modelling of processes that control water quality and setting safe levels. • (medical) toxicology — particularly identifying effluents damaging to human health. • biodiversity and land use • health and ecotoxicology — particularly green chemistry Also required: additional collaboration between anthropology, behaviour science, material science, textile technology, etc.
Interventions	Assessment of ecosystem shift towards bio-based technology through dedicated research is required, including a collaborative initiative mapping anticipated future flows of materials, stakeholders and the economic case for an ecosystem shift towards bio-based solutions.

4.4 Circular design and business models

Identifying promising design and technical interventions, business models and enabling conditions to address current issues in the fashion and textiles sector.

Industry needs and recommendations

A variety of promising technical interventions can be incorporated for the fashion industry to move towards a **zero-waste model**. These include interventions such as sharing fabrics across multiple garments and distributing offcuts across a capsule of styles.

Designing for one-size-fits-most and incorporating adjustable elements (like tie waists) helps create shape and adjust fit for different wearers, using fullness, gathers, pleats, darts or tucks to create shape, instead of panels or offcuts. Start the design process by considering the fabric width first and cut on crosswise grain to get pieces to fit together, as well as adjusting seam or hem allowance to enable a zero-waste pattern to work.

It would also be beneficial to **manufacture more than one size at a time** and **manufacture at scale**. There are also interventions that can be employed to increase the lifetime longevity of a garment. These include identifying which garment areas are most likely to need reinforcement-through **durable construction methods** and reinforcing these areas and stress points. Using linings, facings, gussets, yokes, taping or fusing can help to strengthen the product, ass well as incorporating stronger seam or construction types, such as lapped, welt, bound or overlocked seams, cementing, bonding or gluing. Durable trims that won't break before the fabric wears out should be incorporated.[112]

The lifetime of a garment can be prolonged through advising the consumer about **better laundry and care methods** such as washing at lower temperatures and, where possible. less often. Avoid tumble drying. Provide or recommend repair services, or provide trims and guidance so the user can fix the product themselves. Use alternative finishes that make caring for the garment easier.

Circular business models such as **rental and subscription** (if designed with sustainability principles), **product take-back and service, recommerce, remanufacture** and **upcycling** can all be used to address current issues in the fashion and textiles sector. Reducing emissions from brands' own operations through **alternative materials, sustainable transport, improved packaging, decarbonising retail operations** and minimising returns and over-production would all be beneficial.[113]

All of the brands interviewed are trying to integrate environmental considerations into the design process to enable impact minimisation at the

112 ASOS and Centre for Sustainable Fashion, UAL (2021) ASOS Circular Design Guidebook. Available at: https://asos-12954-s3.s3.eu-west-2.amazonaws.com/files/9516/3766/4620/asos-circular-design-guidebook.pdf
113 McKinsey & Company and Global Fashion Agenda (2020) Fashion on Climate. Available at: https://www.mckinsey.com/~/media/mckinsey/industries/retail/our insights/fashion on climate/fashion-on-climate-full-report.pdf

outset. Some have developed and published their own set of circularity or sustainability tools, strategy and guidelines (John Lewis, ASOS, H&M, etc). However, it is extremely difficult to design for a system that is not yet fully functioning.

Design for recycling is challenged by a lack of agreed material input specification from recovery processes in development. EOL recovery technologies in development could be better understood across the supply chain to develop a set of best practices.

4.4.a. Integration of environmental assessment in the design process (env-data- driven design)

Environmental science has a vital role in informing the design of new textile products and apparel at the earliest possible stages and quantifying impacts of uptake of circular strategies set out in the F&T sector.

Industry pull / market failure
Blue = environmental science source

Industry challenges include:

- establishing industry averages to assess environmental impacts that avoid misleading comparisons between material choices
- developing new comparative models for understanding a spectrum of impacts (best to worst case) for common fibre groups
- using machine learning and algorithmic decision-making to design new chemistry, polymers and materials within set environmental criteria
- establishing methods of designing to mitigate impacts, enhance recyclability and encourage sustainable behaviours informed by environmental science

- building open-source tools for communicating LCA and other impact assessment methodologies for FTT design and specification teams
- engaging creative computing and informatics to communicate complex environmental effects within the design process
- assessing circular strategies as set out through industry initiatives (e.g. H&M, John Lewis, ASOS) against environmental impact criteria.

“When we’re looking at circularity in all of the different principles, it’s extremely complex. We’re criticised quite a lot. Formerly, each product only had to hit two out of the eight principles to be considered circular. But in fact there are some products where it’s not possible to hit all of those eight principles. It’s always a trade off and just making the best decisions that you can at the time…our circular principles initiative is currently very much internal, but we’re about to engage with a third party to verify the work that we’ve done. We’ve reached out to a combination of consultancy and academic institutions — we definitely see the benefit of working with academic research. So much of the Circular Economy is based on innovation and innovation comes from research.”

	"In order to take into account all aspects, we need to start by understanding the product purpose. What is that product going to be used for, and how long is it going to be around for, and what is the frequency of use? Because that would very much determine what you need to focus on most. So how do you optimise resources and balance between material impact and product longevity, which is connected to understanding a garment's purpose (archetypes). We've been trying to develop a matrix to weigh that up as part of our circular design programme."
Opportunity	**This represents a pre-competitive opportunity:** many new data-tech businesses are appearing (with significant private sector investment). There is an opportunity for the UK to lead in this emergent commercial sector, and to impact positively on global supply chain actors.
Research questions Blue = research questions with a leading environmental science component	• **How can industry averages be standardised to allow environmental assessment to be managed across the sector?** • **How can we understand the major fibre groups (used in apparel) across a range of environmental impact factors?** • **How can environmental performance be built into new materials through AI and computer modelling of data?** • **How can sustainable behaviours be encouraged, informed by environmental science?** • **Could open-source assessment tools be developed with new methods for use in order to increase their application across the sector?** • **How can product purpose be built into LCA models in order to establish appropriate criteria for comparison?**
Environmental science contribution	**Addressing research gaps will require environmental expertise in:** • environmental informatics – particularly LCA standardisation and LCA methodologies, including social factors. Also required: additional collaboration between design research, material science, textile technology, etc
Interventions	An interdisciplinary intervention to review existing methodologies and find models for understanding a spectrum of impacts (best to worst case) for common fibre groups.

4.4.b. Designing textiles and products for longevity, reduced waste and specific recycling routes (including emerging technologies)

A key feature of circular design is desining new products that fit the specifications of various exisiting (and emerging) recyling processes, but there is no agreed standard or tolerance levels for contamination (including non-recyclable fibres and additives).

Industry pull / market failure
Blue = environmental science source

Industry challenges include:

- scaling novel production models such as made-to-measure, on-demand manufacturing, onshoring and tracking technologies, all of which show promise (though clarity on true environmental benefits is still under-researched)
- assessing circular business models in relation to mitigation of impacts on the environment and social impact indicators
- developing new methods for a connected and collaborative approach to circularity
- transparency of available and emerging recycling processes in relation to specifications for design-for-recycling approaches
- zero-waste interventions (one-size-fits-most, designing to fabric width, manufacturing multiple sizes simultaneously and at scale)
- Increasing garment longevity through reinforcement of heavy-wear locations and using durable construction methods.

“[With new circular business models], it’s actually a case of prioritisation because we have a lot of [business] teams who are calling out for take-back schemes or rental repair. And so at the moment it’s a case of trying to identify which should be the priority. I think we see fashion take-back or fashion buyback as probably the the quickest or easiest win, but in the long term we want to have circular business models available in all product categories.”

“The key with more circular models is to make them as easy and even more attractive than the linear model to the customer. We recently launched a resale section in the Swedish market and we’re now looking at how we scale that for other markets, really focusing on the customer experience.”

“Transparency and traceability is a major challenge right now, but also could be a huge enabler in the future. If we’re going to transition to a circular model at scale, what is going to be the social impact? We were part of a project recently looking at blockchain and transparency, looking at production workers, store workers and product development teams as well as logistics, mapping different circular models and how they might evolve in different directions.”

Opportunity	**This represents a pre-competitive opportunity:** brands are eager to quantify efforts to extend lifetime of product in order to improve performance through design. If achieved, benefits would include better customer satisfaction, profitability, and improved environmental credentials.
Research questions **Blue = research questions with a leading environmental science component**	• **How can circular business models such as rental and subscription, product take-back and service, recommerce, remanufacture and upcycling/repair be evaluated within a robust LCA framework?** • **How can brands access more verified information on different parts of the material life cycle?** • **How can environmental assessment metrics be incorporated into digital manufacturing systems (e.g. Unmade's technology) to inform design for manufacture principles?** • **Can non-physical as well as physical durability be assessed in LCA metrics?** • Can more durable trims be developed that are recyclable and won't break before the fabric wears out? • How can brands work directly with producers of circular materials and recycling technology developers to understand potential blocks in the system created through design and material specification?
Environmental science contribution	**Addressing research gaps will require environmental expertise in:** • environmental informatics – particularly LCA standardisation and LCA methodologies, including social factors. Also required: additional collaboration between design research, material science, textile technology, etc.
Interventions	Research that combines circular design principles and industry R&D with environmental assessment in real time could be achieved through pilot programmes (NERC, IUK and EPSRC) to drive innovation in real-world contexts, while developing novel methodologies for accelerated impact.

4.5 Interdisciplinary research methods

Fostering interdisciplinary approaches toward complex circular research outcomes and accelerated progress

Industry needs and recommendations

In general, **interdisciplinary approaches are recommended to inform complex single industry can solve the current issues in the fashion and textiles sector alone**. This approach could involve shared research themes, across research councils, with programmes that allow collaboration over a longer timeframe (e.g. follow-on funding for successful projects).

The strategic joining up of cross-council delivery plans to enable end-to-end investigation of potential solutions could provide foundations for accelerated results (for example, in the development of bio-based innovation, there would be benefit for BBSRC, NERC and even IUK to connect at different TRL points in the research and innovation timeline). Environmental science defining new areas of concern is imperative as a means of measuring harm and beginning a process to find solutions.

Systems for optimised recirculation can be developed through textile and clothing collectors working with recommerce platform providers, brands and digital innovators. Development of technological systems that enable used clothes to be rerouted via integrated channels will maximise the life and utilisation of each individual item. For example, brands and platform providers could collaborate to integrate information and photography from original product listings, to provide the next user a view of the provenance and journey of individual garments. This could be achieved by expanding solutions for enhanced identification and tracking. Standardised local authority collection systems would accelerate progress. This would require government to work with institutions, industry bodies and the third sector to implement and improve kerbside textile collection, sorting, and recycling.

It is important that the UK demonstrates the value of and drives investment in efficient textile sorting facilities, as well as phased scaling of open-loop, closed-loop and regenerative recycling. However, if these systems are to become efficient, the government will need to conduct a feasibility assessment and consultation for phased scaling within the UK. A roadmap informed by industry, academic and civil society research will need to be conducted into the systemwide environmental impacts of scaling chemical recycling. Technical solutions that enable high value fibre-to-fibre recycling should also be explored. Scaling activities should take into consideration the transition to renewable energy within the UK.

Institutions, industry bodies and the third sector must collaborate with government on investing in, promoting and implementing the upskilling of workers to meet the demand for sortation and recycling that will emerge. As new sorting and recycling technologies are developed, there will be a need for technicians, technology developers, engineers and manual sorters, who will all remain crucial for finer sorting, even with increases in automisation. Greater logistics expertise is also required across the sector.

The government would also be required to bring together multi-stakeholder initiatives, with brands and reprocessors, to coordinate investment into new sorting technologies, e.g. near-infrared (NIR), as well as large-scale facilities for their implementation. Technologies that can sort according to fibre composition and colour are vital. Used clothing must also be appropriately pre-processed through cleaning, removal of hardware, and product disassembly.

The UK also requires dedicated research and a collaborative initiative aimed at mapping the anticipated future flows of materials, as well as defining who would be involved and the economic case for an ecosystem shift towards regenerative recycling. To do so, this requires institutions, industry bodies and the third sector to lead a project dedicated to modelling the detailed economic and material flows of a future circular ecosystem for UK fashion.

Manufacturers may also want to consider a multi-stakeholder initiative, including brands and government, to support and develop garment manufacturing in the UK, focusing on facilitating fundamental conditions for fair and decent work for all workers, as well as the utilisation of recycled inputs for UK manufacturing. Doing so should incorporate research into the drivers of the success of some UK retailers in expanding domestic manufacturing, as well as aiming to understand the capabilities, technology, capacity, and skills that the UK will require for development within its infrastructure and workforce.[114]

4.5.a. Development interdisciplinary approaches for complex collaborations

New interdisciplinary approaches are needed for complex circular research outcomes and accelerated progress within academic research and the industry.

Industry pull / market failure **Purple = environmental science source**	**Industry challenges include:** • interdisciplinary approaches to complex circular research outcomes • institution, industry bodies and third-sector collaborations with government on investing in, promoting and implementing the up-skilling of workers • dedicated research and collaborative initiatives, aimed at mapping out anticipated future flows of materials and the economic case for regenerative recycling • multi-stakeholder initiatives, including brands and government, to support and develop increased garment manufacturing in the UK • shared insight towards environmental impact improvements between brands (usually considered competitors).

114 Environmental Audit Committee (2019) Fixing Fashion: Clothing Consumption and Sustainability. Available at: https://publications.parliament.uk/pa/cm201719/cmselect/cmenvaud/1952/1952.pdf

	"As soon as you enter into sustainability, companies are a lot more open and willing to share. So we're definitely engaging with people that we would consider competitors. Working with organisations like WRAP, everyone is working towards a common goal, and willing to share progress and insights. And we find that brands and retailers are quite open with sharing their experience with us as well." **"There is insufficient connection between the regulatory environment and the innovation environment, and so if NERC scientists discover a harmful compound there is no automatic way by which EPSRC can quickly trigger research on finding alternatives. This part of the system is really, really inefficient…progress is not made quickly enough because there's no connectivity between the regulatory problem, the environmental problem, and the potential solution finding alternatives to that nasty chemical."**
Opportunity	Rather than a specific commercial opportunity, this theme represents the engine to drive forward impact in the CF&T sector and is the basis for many of the complex collaborations required to address challenges outlined in other sections (4.1.a, 4.2.a, 4.4.a, 4.4.b.).
Research questions **Purple = environmental science source**	• How can we convene disciplines that share strategies for sustainability and circularity (e.g. guidelines in CF&T industry translatable to the 12 Laws of Green Chemistry)? • How can we study new biotech-based novel fibres, dyes and textile chemicals from renewable biological feedstocks, to substantially reduce microplastic and textile chemical pollution? • How can we develop multi-disciplinary approaches involving textile technologists, synthetic chemists, process engineers, microbiologists and biotechnologists? • How do we systematically study the fate, transportation, and effects of non-degraded and degraded textile dyes and chemicals on human health, terrestrial and marine ecology, conservation and biodiversity? • How do we adopt multi-disciplinary approaches involving process engineers, chemists, toxicologists, biologists, soil ecologists, and more? • How do we adopt transferable methodologies across the scales of industry, from micro, small and medium enterprises to global brands? • How do we embed proactive and mitigating approaches upstream in R&D? • How should manufacturers consider multi-stakeholder initiatives that include brands and government, to support and develop garment manufacturing in the UK?

	• How can institutions, industry bodies and the third sector collaborate with government on investing in, promoting and implementing the upskilling of workers? • **What methods can enable rapid establishment of interdisciplinary collaboration?** • **How can we embed multi-factor impact analysis of production methods as they are scaled through TRL stages?**
Environmental science contribution	**Addressing research gaps will require environmental expertise in:** • all disciplines included in 4.1–4.4.
Interventions	Interventions should be attached to those presented in 4.1–4.4, alongside research programmes, either as a component of the research or as a focus across a collaborative programme of activity.

5
Theory of Change

Producer of anti-viral and anti-bacterial coatings

Cross-UKRI intervention in the area of circular fashion and textiles with effective contribution of environmental science

IMPACT

Improved understanding of environmental issues in CF&T sector and strengthening of UK research and innovation base

Clean growth of textile supply chain & technologies or UK markets	Environmental impacts of fibre & chemical loss reduced	Innovative fibre & recycling technologies strengthened	Circular & sustainable business models developed	New methods developed for interdisciplinary research

OBJECTIVES

4.1 Supply chain impact reduction	**4.2 Fibre & chemical loss**	**4.3 Innovative fibre & recycling tech**	**4.4 Circular design & business models**	**4.5 Interdisciplinary research**
Design alternative manufacturing and chemical processes to minimise environmental degradation and preserve natural resources	Building systematic understanding and mitigation of the primary chemical and fibre leakage points accross the value chain for textile applications important to the UK economy	Ensuring that circular fibre technologies (for both bio-based and synthetic materials) bring substantial environmental benefits accross all impact categories and prevent regrettable substitutions	Identifying promising design and technical interventions, business models and enabling conditions to address current issues in the fashion and textiles sector	Fostering interdisciplinary approaches toward complex circular research outcomes and accelerated progress

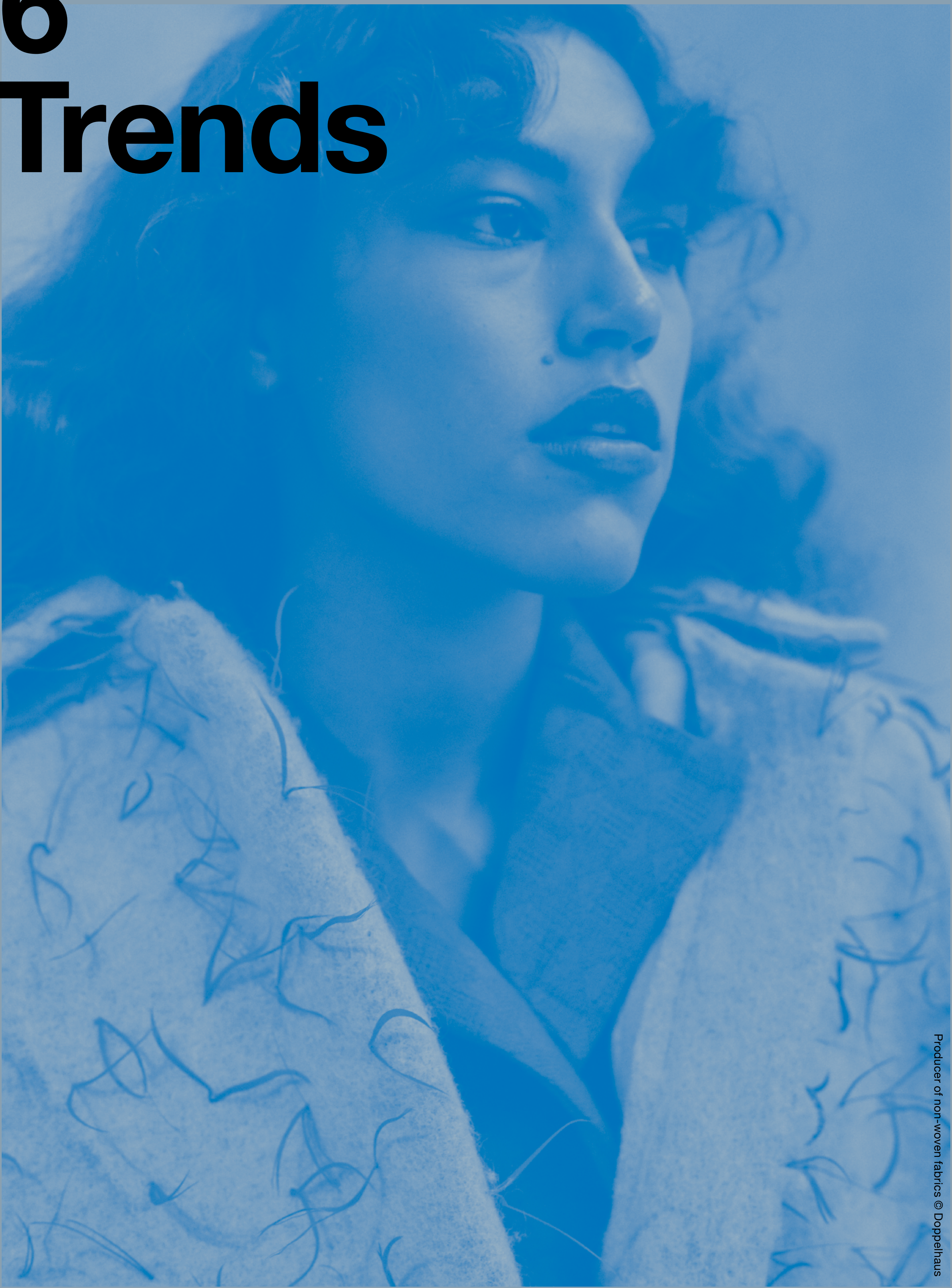
ACTIVITIES

4.1.a Measures to address pollution and toxicity in materials and manufacture **4.1.b** Life cycle analysis of environmental impacts throughout the supply chain	**4.2.a** Environmental effects of textile fibre and chemical loss **4.2.b** Measures to prevent fibre and chemical loss during production, use and disposal	**4.3.a** Profilling of impacts and chemicals in novel fibre recycling technologies **4.3.b** Assessment of emerging biological manufacturing technologies	**4.4.a** Designing textiles and products for longevity, reduced waste and specific recycling routes **4.4.b** Integration of environmental assessment in the design process	**4.5.a** Development pf interdisciplinary approaches for complex collaborations

TARGET GROUPS

• Apparel & fashion brands • Textile manufacturers & designers (yarn, textile and garment) • Computing and creative comms • Data scientists and analysts • Chemistry, chemical process engineers • Design researchers	• Textile manufacturers & designers (yarn, textile and garment) • Washing machine manufacturers, brands and retailers • Wastewater scientists, chemical process engineers	• Collector and sorters • Environmental scientists, chemists, chemical process engineers, material/ polymer, scientists	• Design researchers, brands and retailers • Computing and data visualisation • Data analysts • Environmental scientists, chemists, chemical process engineers	• Academic disciplines accross the value chain (science, design & technology) • Textile manufacturers & designers (yarn, textile and garment) • Social scientists and anthropologists • FTT industry representatives from brands, SMEs, micro-businesses and marketing

6
Trends



Producer of non-woven fabrics © Doppelhaus

6.1 Emerging environmental, political and social trends

Environmental

Climate change, now frequently referred to as climate emergency, is seen as the most pressing global challenge over the next decade. The Intergovernmental Panel on Climate Change (IPCC) recently reported that many impacts will be more severe than previously predicted, with only a limited opportunity now to avoid devastation.

The IPCC reports that if we allow our global temperatures to rise by more than 1.5oC over pre-industrial levels, as predicted by current trends in greenhouse gas emissions, this will result in irreversible impacts.[115]

With humans causing unprecedented, irreversible changes to the Earth's climate, scientists warn that every inhabited region will be affected, with half the earth's population living in highly vulnerable areas. Even at current heating levels, it is predicted that millions of people will face food and water shortages owing to climate change, while mass extinction of species from trees to corals has already begun. Ecosystems are losing their capability to absorb carbon dioxide, transforming them from carbon sinks to carbon sources. Additionally, 50 countries have agreed to conserve 30 percent of the Earth's land[116], though the IPCC reports that conserving half could be required just to restore the ability of nature's ecosystems to cope with the damage inflicted on them.

While we are now beginning to understand more about the climate emergency, it is still estimated that the fashion and textile industrial sector produces up to 10 percent of global CO2 emissions each year, and is also the second largest water consumer globally. Additionally, research suggests that the industry produces approximately 92 million tonnes of textile waste annually, which either ends its life in landfills or incineration.[117]

The Ellen MacArthur Foundation reports that under 1 percent of the textiles manufactured for application in apparel are later recycled into new garments, and 87 percent of materials utilised for apparel manufacture is either landfilled or incinerated after definitive use.[118] This represents a lost opportunity of over $100 billion (€84 billion) each year,[119] which could otherwise be invested back into the UK. To live in a Circular Economy, we must tackle the root causes of global challenges such as climate change, biodiversity loss, waste and pollution, while creating opportunities for increased growth [120].

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115 Intergovernmental Panel on Climate Change (IPCC) (2022) Climate Change 2021: The Physical Science Basis. Available at: https://www.ipcc.ch/report/ar6/wg1/
116 Available at: https://www.campaignfornature.org/50-countries-announce-bold-commitment-to-protect-at-least-30-of-the-worlds-land-and-ocean-by-2030 (Accessed: 11 October 2022).
117 Quantis (2018) Measuring Fashion: Insights from the Environmental Impact of the Global Apparel and Footwear Industries Study. Available at: https://quantis-intl.com/report/measuring-fashion-report/
118 Ellen MacArthur Foundation (2017) A New Textiles Economy. Available at: https://ellenmacarthurfoundation.org/a-new-textiles-economy
119 Piippo, R., et al. (2022) Fit for the Future: Garment Quality and Product Lifetimes in a CE Context, *Sustainability*, 14(2). Available at: https://www.doi.org/10.3390/su14020726
120 Ellen MacArthur Foundation (2020) The Jeans Redesign Project. Available at: https://www.ellenmacarthurfoundation.org/our-work/activities/make-fashion-circular/projects/the-jeans-redesign

Political

While many countries are rebounding from the economic downturn brought on by the Covid-19 pandemic, global supply chains are facing lasting strains such as factory shutdowns, widespread lockdowns and mobility restrictions.[121] These have each prompted changes in consumption patterns, rising demand for goods and shortages of workers. Current political pressures, including Brexit and the war in Ukraine have in turn created shipping delays. Each factor influences a combination of high shipping volumes and rising freight costs, with analysts predicting that disruptions will be persistent; economists from the Federal Reserve have developed a new analytical tool, the Global Supply Chain Pressure Index, to analyse exactly how much pressure is on global supply chains.

The Global Supply Chain Pressure Index uses 25 years of data and a wide range of metrics to map, measure and manage the negative impacts that are consistently being inflicted on the global supply chain and economy. Results found that during the pandemic, supply chain pressures increased significantly, exceeding any predicted trend lines. This includes soaring shipping costs, with the global going rate of a 40-foot container leaping from $1,400 in early 2020 to more than $11,000 in September 2021.

It is predicted that in the long term, shipping container rates will rise more than 50 percent, a significant increase compared with the last biggest rise of 14 percent above the long-term trend following the global recession caused by the 2008 financial crisis. This data demonstrates the importance of supply chain professionals, policymakers and business leaders advocating for and implementing reshoring manufacturing back to the UK, to eliminate obstacles caused by political and environmental pressures, and importantly ensuring more sustainable practices. This should be accompanied by the scaling up of digital methods within the supply chain, enabling UK businesses to become more agile, less wasteful, and responsive, in light of environmental changes.[122]

Social

In recent years, sustainability has evolved into a crucial driver of how the consumer decides to purchase. With the global population growing and climate change as well as land and water scarcity being magnified, sustainability pressures related both to product and production processes have become increasingly relevant in this industry.[123]

Generation Y, also known as Millennials, born between 1980 and 1994, are the largest group of people currently at work, representing 35 percent of the total workforce. Studies show that affluent Millennial consumers would like their preferred fashion brands to get involved with, and provide positive contributions to their ecosystem with practical actions, and are

121 https://www.ons.gov.uk/businessindustryandtrade/internationaltrade/articles/earlyinsightsintotheimpactsofthecoronaviruspandemicandeuexitonbusinesssupplychainsintheuk/february2021tofebruary2022 (Accessed: 11 October 2022).

122 Benigno, G., di Giovanni, J., Groen, J.J.J., and Noble, A.I. (2022) 'A New Barometer of Global Supply Chain Pressures', *Liberty Street Economics* (4 January). Available at: https://libertystreeteconomics.newyorkfed.org/2022/01/a-new-barometer-of-global-supply-chain-pressures/

123 Gazzola, P., et al. (2020) Trends in the Fashion Industry. The Perception of Sustainability and Circular Economy: A Gender/Generation Quantitative Approach, *Sustainability,* 12(7). Available at: https://doi.org/10.3390/su12072809

happy to pay a premium cost for products that come from sustainable brands.[124]

As this generation values transparency and authenticity, they believe that the brands from which they purchase should reflect their own values. This generation is more socially and environmentally conscious than the previous generation, and in turn expects more from fashion brands in terms of sustainable and ethical production processes. This is important to note for brands wishing to attract and retain this market segment.[125]

Generation Z, born after 1995, have known only economically turbulent and digital-first social conditions. This generation entering the workforce will radically change the nature of business, in terms of approaches to work, and modes of consumption. Recent studies have begun to uncover Millennial and Generation Z attitudes to quality when making purchases. One study found that 60 percent cited the quality of garments and accessories as more important than a reduced price. The data for this report was based on a sample size of 2,424 respondents, 39 percent of whom were Millennials and 63 percent were Generation Z. The youngest category of respondents also indicated that they were willing to face an increased price tag for sustainability, with 37 percent happy to pay an increased cost for a responsibly produced item.[126]

There is also some suggestion that gender influences sustainability-driven social action and opinion. Women, particularly within the age bracket between 18 and 34 years, with a higher qualification and an occupation as a student, employee, or teacher, are typically more knowledgeable than men about the applications of sustainability principles within a variety of fields.[127] Nonetheless, given rapid policy and technology developments in the field, which in turn inform social attitudes, more research is needed to understand sex-based differences in sustainable fashion and textile consumption behaviour.[128]

6.2 Emerging industry and technological trends

A 2021 Material Innovation Initiative State of the Industry report[129] describes the increased viability of next-generation materials, which use fewer resources and produce less waste, and are animal-free and high-performance. The report identified 74 next-gen material companies, which had collectively received $1.29 billion of investment. It identified 38 out of 40 leading fashion brands as actively searching for next-gen materials.

Fibre-to-fibre recycling technologies: recycling companies from the

124 https://www.catalyst.org/research/generations-demographic-trends-in-population-and-workforce/ (Accessed: 11 October 2022).
125 First Insight (2019) The state of consumer spending: Gen Z Shoppers demand sustainable retail. Available at: https://www.firstinsight.com/white-papers-posts/gen-z-shoppers-demand-sustainability
126 https://www.pwc.com/it/it/press-room/assets/docs/cs_pwc_food.pdf (Accessed: 11 October 2022).
127 Brough, A.R., et al. (2016) Is Eco-Friendly Unmanly? The Green-Feminine Stereotype and Its Effect on Sustainable Consumption, *Journal of Consumer Research,* 43(4), pp.567–582. Available at: https://doi.org/10.1093/jcr/ucw044
128 British Fashion Council/Institute of Positive Fashion (2021) The Circular Fashion Ecosystem: A Blueprint for the Future. Available at: https://instituteofpositivefashion.com/uploads/files/1/CFE/Circular_Fashion_Ecosytem_Report.pdf
129 Material Innovation Initiative (2021) *State of the Industry Report: Next-Gen Materials.* Available at: https://www.materialinnovation.org/state-of-the-industry

UK, Europe and the Far East represent around 20 examples of recycling technologies for synthetic, cellulosic and even protein fibres.[130] Only a small number of these companies can deal effectively with blended textile inputs and most can only process monomaterial inputs.

Worn Again[131], the leading UK recycling technology company, is currently at pilot scale at its plant in Redcar, UK. Its process converts used polyester and polycotton blended textiles, and PET plastic, back into circular raw materials. Worn Again is able to separate, decontaminate and extract polyester and cellulose (from cotton) from non-reusable textiles and polyester bottles and packaging to produce dual PET and cellulose outputs.

The Green Machine[132] was developed by HKRITA, with support from the H&M Foundation. The first commercial order was made by Kahatex, the largest textile manufacturer in Indonesia, in 2020. In 2021, the world's biggest denim producer, **ISKO, ordered one** for its factory in Turkey and the same year **a consortium of key actors in the textile sector, including GIZ, VF Corp and Dakota, joined forces** to launch a feasibility study to deploy the Green Machine in Cambodia by 2022.

Recover[133], a leading producer of high-quality recycled cotton fibre and blends, started the scaling up of its recycling technology in 2021. Polycotton waste will be more than 40 percent of its material input by 2025, recycling around 425 million garments and increasing production to 200,000 metric tonnes of recycled cotton fibre per year by 2025. The first hubs are set to open in Bangladesh and Vietnam in 2022.

Apparel and fashion sector's increased commitment to recycled materials: fashion brands from across the market spectrum are communicating ambitious goals for increasing their use of recycled materials in their textile products. Chemically recycled materials are not yet mainstream, but alternative recycled content that can meet strict quality standards is increasing.

H&M Group[134], the global clothing group that includes H&M, COS, Monki, Weekday, & Other Stories, Cheap Monday and ARKET, pledged that 30 percent of its total materials will be from recycled sources by 2025. In 2020 it achieved 64.5 percent recycled or other more sustainably sourced materials, compared to 57.1 percent in 2019.

Kering[135], the global luxury group that includes Gucci, Saint Laurent, Bottega Veneta, Balenciaga and Alexander McQueen, published its circularity ambition with strong commitments such as zero microfibre leakage by 2030 and zero unsold product destruction.

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130 Goldsworthy, K., and Hornbuckle, R. (2022) Business of Fashion, Textiles and Technology: Circular Synthetics Report, University of the Arts London. Available at: https://bftt.org.uk/publications/
131 https://wornagain.co.uk/ (Accessed: 11 October 2022).
132 https://hmfoundation.com/project/recycling-the-green-machine/ (Accessed: 11 October 2022).
133 https://recoverfiber.com/ (Accessed: 11 October 2022).
134 https://www2.hm.com/ (Accessed: 11 October 2022).
135 https://www.kering.com/ (Accessed: 11 October 2022).

Primark, the international high-street clothing brand partnered with recycling company **Recover** to create sustainable fashion at affordable prices, under the Primark Care label.[136]

Large brands prioritising circularity: design from the outset should begin with circularity as an approach. Several large fashion brands have produced circular tools and guidelines, including ASOS, John Lewis and H&M.

H&M is working on circular product development guidelines to empower its teams to create more circular products, enabled from the drawing board to circulate within a future circular ecosystem.

Reformation has launched a denim that focuses on durability, material health, recyclability and traceability and is made to be circulated, not wasted. Its FibreTrace™ collection features a first-of-its-kind fibre traceability technology that embeds luminescent pigments into the fabric, showing the whole lifecycle of the jeans.

Reformation also relaunched Ref shoes in March of 2021; 100 percent of Ref Shoes 2.0 are designed to be recyclable. It has partnered with Looptworks to create a first-of-its-kind takeback programme, planned for launch in October 2022.

Brand collaboration: There are some interesting cross-disciplinary partnerships emerging across brands, maximising circularity potential.

Finisterre[137, 138] successfully launched its Lived & Loved trade-in platform during 2021, building on its established repairs service, allowing customers to get credit for trading in their old clothes in partnership with Reskinned. What cannot be resold is sorted for textile upcyling and eventual fibre-to-fibre recycling. The ambition is to maximise product lifespan and enable multiple ownership.

H&M increased focus on resale with the Sellpy second-hand shopping platform, now available in over 20 markets.

Worn Again participated in a number of collaborative industry initiatives and working groups which seek to overcome key market barriers and pave the way for textile-to-textile recycling, including Accelerating Circularity, the British Fashion Council's Circular Fashion Ecosystem, and Reverse Resources' Circular Fashion Partnership.

Beyond Retro built on its relationship with Renewcell. They are now on track to supply 18,000 metric tonnes of post-consumer denim by May 2022, to be recycled into Circulose.

Feedstock provision and reverse logistics: waste streams are being valorised with technology and a local perspective.

136 https://www.primark.com/en/primark-cares (Accessed: 11 October 2022).
137 https://finisterre.com/pages/lived-loved (Accessed: 12 October 2022).
138 https://takeback.reskinned.clothing/finisterre (Accessed: 12 October 2022).

Dibella set up reverse logistics for collecting and distributing post-consumer/laundry textiles to different initiatives such as Södra and Reused Remade.

Asics produced Japan's Olympics 2022 sports kit — recycled clothes were donated by people across Japan for the team.

EON is working with brands to digitise and connect garments online with a digital ID, to ensure products and materials can be managed through a circular lifecycle.

SATCO kept all its clothing bank collections running throughout Covid-19 lockdowns and in January 2021 opened a modern, purpose-built processing centre in the Midlands, UK. This centre contains state-of-the-art materials handling equipment and sorting conveyors with an automated, advanced fibre sorting line for reprocessing textiles for recycling. This innovation (part-funded by the UK Government's Resource Action Fund) will enable accurate sorting and grading of non-rewearable clothing and textiles by fibre type, fibre blend and colour for recycling into the circular textiles supply chain. In 2022 it developed a Carbon Reduction Plan and Circular Economy Strategy and is using the Ellen MacArthur Foundation Circulytics tool to help guide it towards circularity.

Beyond Retro finds homes for clothing in the reuse space across its wholesale, vintage retail and innovation hub, saving over 250 million garments from landfill in 2021. It opened four new stores in Europe despite the pressures of global lockdown.

Recycles high-value fibres from fabric waste into spun yarns

7 Conclusion

7.1 The role of environmental science research in Circular Fashion and Textiles

- **To pre-empt and prevent environmental harm before it occurs.**
- **To provide a clear translation of evidence to inform decision-making and change behaviour.**
- **To provide the 'voice of the environment' as an integrated stake-holder in any novel solution development.**

The **number one aim of engaging environmental science** should be to pre-empt and prevent potential impacts on the environment due to new materials, processes and actions **before the damage occurs**. This is a position unique to NERC and should be at the core of any challenge in the area of circular and sustainable fashion, apparel and textiles. There is a danger that if environmental science is not engaged at an early stage in technology development (R&D) then the opportunity to **avoid developing future harms and unintended consequences is missed**.

The second important role that NERC can provide is **clear translation of evidence to the stakeholders engaged in decision making** as well as to the consumer. There is a huge amount of confusion in an extremely complex arena and NERC could be pivotal in making solid **science available and accessible** to those who can act upon it.

Thirdly, the **environment must be considered as a participating stake-holder** with **environmental science providing that voice** within the challenge themes outlined in Section 4. These are the main areas of emerging and essential activity in order to create a viable CF&T ecology (not only economy).

7.2 Priority research questions

These questions (and sub-questions) point to work needed in the environmental sciences to build a CF&T industry that is fit for purpose. They can be seen as cross-cutting and may relate to more than one of the challenge themes described in Section 4.

Understanding environmental benefits (and risks) of co-locating fibre crops and novel processing solutions

Use of natural resources *in relation to* land use *and the* degradation of environmental habitats *needs to be considered at the start of any process to increase the production of fibres that requires agricultural resources.* Untested chemical combinations*, specifics of* geographical environmental factors *and beneficial conditions of* co-location of processes *are key.*

- How might environmental science be engaged to prove mutual benefit from multiple agri-tech activities or co-location of processes (e.g., cotton is often grown with tomatoes)?
- What impacts might there be to wildlife environments due to co-location that might not exist if each process was located separately?
- What would the impacts of potential leakages from fashion and textile

production systems be in the natural seascape or water infrastructure?
- What effect does the geographical location of these processes have on the likely impact on contextual habitats?
- To what extent do chemical ecosystems (multiple chemicals interacting in the FTT space) lead to unexpected environmental effects on terrestrial or oceanic environments?
- How do textile-specific chemicals interact with the natural environment over time in specific contexts (land, freshwater, saltwater, etc).

Understanding supply chain design, circular business models and interdependencies in relation to environmental impact

The complexity of fashion and textile supply chains *are often described as* a 'system of systems'*. This system is* globally active and open to constant change and review*. Local systems are broadly understood to offer resilience and environmental improvements, but they are* largely untested in environmental science *research.*

- How can more 'local production', as part of the global fashion and textiles supply chain, best meet environmental challenges (e.g., carbon, biodiversity, water and land use)?
- To what extent is it better to locate manufacture nearer to the market as opposed to nearer the raw materials?
- What are the tensions/benefits across carbon, biodiversity, water and land use in circular and sustainable substitution decision points?
- How can these tensions/benefits be modelled to provide an evidence base to inform positive change and action.

Valorisation and recovery of waste

A potentially exciting area of research is emerging around recovery linking through to new product systems *in one location. How can waste be* valorised at the point of recovery *and to what degree do those processes benefit the natural environment or* tackle the carbon targets*?*

- How can waste recovery processes and associated energy demands be measured in order to fully determine impact (positive/negative)?
- How can environmental science help the navigation of complex, multiple, novel waste-related business models, and associated user behaviour?
- How can carbon and other impact factors within the recovery patterns associated with textile waste streams (that are largely unaccounted for in current available data) be accounted for?
- How can the impact of recovering synthetic fibre waste be compared to land-use needs and monocultures associated with bio-based feedstocks?
- How can project losses and gains in natural capital over time be measured using robust modelling and analysis of existing data?

Alternative material choices

In any transition to renewable and sustainable material *sources,* natural capital *should be considered alongside* biodiversity implications *of any* *large-scale fibre production scheme (including cotton, wool and other traditional natural fibres).*

- How can the use of water as a resource during intensive farming of natural fibres be better applied?
- How might the introduction of renewable and sustainable material *sources* and practices interact with monocultures, and what effect might this have on biodiversity?
- What might be the most energy-efficient opportunities for transition to renewable energy during manufacture and production in order to reduce dependence on hydrocarbons and fossil fuels?
- How can natural capital be managed in the most effective and sustainable way with existing practices, and how might this approach reduce fossil-fuel use in real terms?
- Can environmental science provide future-proof, 360-degree analysis of new materials and their potential impact?
- How might the impact of new bio-based materials production be compared to traditional bio-materials (e.g., wool and cotton)? And how might impacts on land use and biodiversity be measured?

Tackling greenwashing and user understanding

There is a role for environmental science in the presentation of best practice and myth busting *across both industry and user stakeholder groups, and the wider public. The* calling out of greenwashing *and aiding understanding are crucial to* encouraging positive behaviour *based on trusted standards, regulation and accreditation.*

- How can environmental science act as a foil to industry greenwashing, and clearly determine the challenges and best solutions?
- How can environmental science provide a framework for measuring the benefits, or disadvantages, of emergent new eco/alternative materials?
- How can environmental science influence decision-makers at the point of design and pre-production of new materials and products?
- How might partnerships across environmental science and economics more positively help to co-create appropriate planning systems and processes?
- How can environmental science provide a framework for materials science research (e.g., in regenerated and recovered fibres), ensuring best practice for the future?
- How can longevity (in the production of materials and products) be assessed via environmental science indicators?
- Can a systems view of resource recovery from textile waste and futures scenario-modelling be achieved?

8 References

Recycles high-value fibres from fabric waste into spun yarns

8.1 Key stakeholders

Expertise across UK disciplines spans ecotoxicology, textiles design (including a thriving technical and e-textiles sector), manufacturing and production, life cycle assessment, Circular Economy, environmental risk assessment, pollution monitoring and human health. This points to significant opportunities in building on recent large investments in related research programmes and national capability towards NERC's strategic themes of global change, and in regulation, enforcement and environmental protection more generally.

Environmental and material science and innovation

UK academic centres of environmental and material science research listed below are active in the area of CE F&T including both design and environmental science perspectives. Most of the centres have specific research areas, such as sustainability assessment of textile products, circular textile design and life-cycle analysis. The Institute for Materials Research and Innovation (IMRI) at the University of Bolton has expertise in sustainable fire-retarding textiles; the School of Design at the University of Leeds and the Department of Materials at the University of Manchester carry out research in wider areas of textile environmental science, including sustainability assessment, sustainable textile manufacturing and microplastic pollution assessment. Scottish Enterprise provided £950,000 funding to Advanced Clothing Solutions to make an innovative garment rental and re-sale business to reduce textile waste.

Circular and sustainable design and production in fashion and textiles

Circular and sustainable design in the UK spans fashion and the Circular Economy, fashion and textiles ecology, materials and anthropology, and fashion and materials science. Some key examples of this approach can be seen in UKRI-funded consortia projects including the UAL-led Business of Fashion, Textiles and Technology (BFTT), CR&DP (AHRC), the EPSRC National Interdisciplinary Circular Economy Research programme, which includes the Textile Circularity Centre based at the Royal College of Art, and EU programmes such as Mistra Future Fashion (MISTRA Foundation), Trash-2-Cash and HEREWEAR (EU H2020).[139]

A list of relevant research centres and institutes is organised into three lead research areas: **environmental sciences**; **material and textile sciences;** and **design and social sciences**.

139 All projects covered in literature review.

Environmental Sciences	• Ecology, biodiversity and systematics • Geosciences • Marine environments • Medical and health interface • Microbial sciences • Plant and crop science • Pollution, waste and resources • Terrestrial and freshwater environments • Tools technology and methods	**Atmospheric Chemistry and Effects department,** UK Centre for Ecology & Hydrology **Centre for Resilience in Environment, Water and Waste (CREWW),** University of Exeter **Department of Chemical & Process Engineering,** University of Strathclyde, Glasgow **Department of Chemistry,** University of Liverpool **Environmental Research Group (ERG),** Imperial College London **Green Materials Laboratory,** University of Manchester **Green Nanomaterials Research Group (GNRG),** University of Sheffield **Living Systems Institute (LSI),** University of Exeter **Macromolecular Materials Laboratory,** University of Cambridge
Material & Textile Sciences	• Polymer and green chemistry • Bio-based material science • Chemical process engineering • Fibre and textile engineering • Synthetic biology and biomimetics • Colouration and finishing technology • Microfibres and microplastic science • Nanotechnology	**Exeter Multidisciplinary Plastics Research Hub (ExeMPLaR),** University of Exeter **Institute for Materials Research and Innovation (IMRI),** University of Bolton **Leeds Institute of Textiles and Colour (LITAC),** University of Leeds **Nonwovens Innovation & Research Institute (NIRI),** University of Leeds **School of Textiles and Design,** Heriot-Watt University **Soft Matter Group (SMG),** Queen Mary University of London **Sustainable Consumption Institute,** University of Manchester **Sustainable Environmental Research Centre,** University of South Wales **Technical Textiles Research Centre (TTRC),** University of Huddersfield

Design & Social Sciences	• Fashion, textiles and technology • Circular, sustainable and social design • Textile and fashion supply chain • CE management science • Political science • Anthropology • Psychology and behavioural science • Systems and service design • Data science and creative computing • Informatics and visual communication	**Centre for Circular Design (CCD),** University of the Arts London **Centre for Sustainable Fashion (CSF),** University of the Arts London **Exeter Centre for Circular Economy (ECCE),** University of Exeter **Fashion, Textiles and Technology Institute (FTTI),** University of the Arts **London Fashion and Textile Research Centre,** Nottingham Trent University **Fashion Business and Technology Group, Department of Materials,** University of Manchester **Manchester Fashion Institute,** Manchester Metropolitan University **Material Science Research Centre (MSRC),** Royal College of Art **Responsible Design Group, Loughborough Design School,** Loughborough University

Table 2. Disciplines engaged in the published research outlined, with aligned research centres and institutes

CF&T Industry Stakeholders

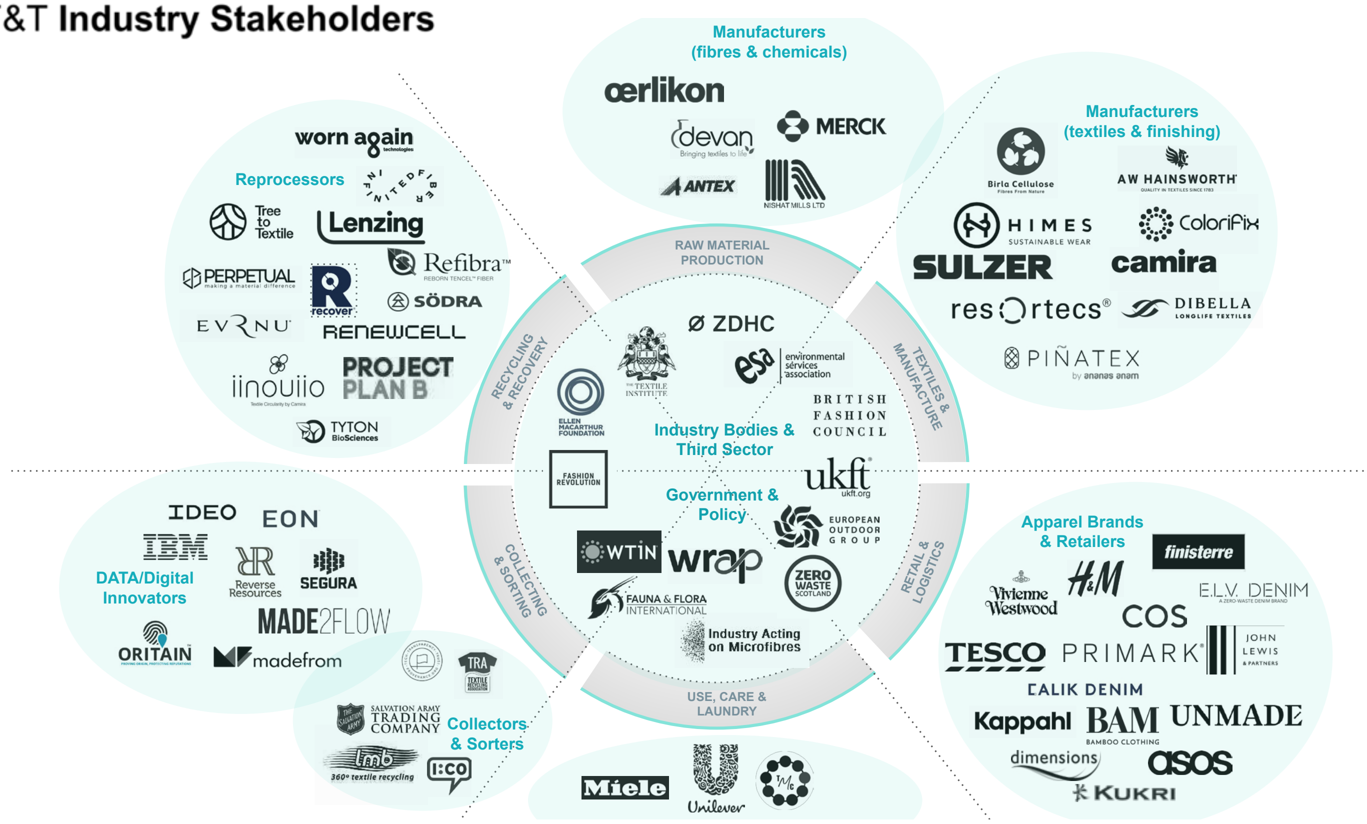

Fig. 4 illustrates the range of industry, government and NGO stakeholders identified during the research.

8.2 Key industry reports

1. **Textiles 2030 Roadmap**, Wrap, https://wrap.org.uk/sites/default/files/2021-04/Textiles%202030%20Circularity%20Roadmap.pdf
2. **Vision of a circular economy for fashion**, Ellen MacArthur Foundation, https://emf.thirdlight.com/link/nbwff6ugh01m-y15u3p/@/preview/1?o
3. **ASOS Circular Design Guidebook**, Asos, https://asos-12954-s3.s3.eu-west-2.amazonaws.com/files/9516/3766/4620/asos-circular-design-guidebook.pdf
4. **The Circular Fashion Ecosystem: A Blueprint for the Future**, British Fashion Council/Institute of Positive Fashion, https://instituteofpositivefashion.com/uploads/files/1/CFE/Circular_Fashion_Ecosytem_Report.pdf
5. **Fashion On Climate: How the fashion industry can urgently act to reduce its greenhouse gas emissions**, McKinsey & Company/Global Fashion Agenda, https://www.mckinsey.com/~/media/mckinsey/industries/retail/ourinsights/fashion-on climate/fashion-on-climate-full-report.pdf
6. **TMC's position on the control of fibre fragmentation, within textile manufacturing wastewater**, The Microfibre Consortium, https://static1.squarespace.com/static/5aaba1998f513028aeec604c/t/6201407a1ff01f0cbb15b908/1644249210577/TMC_Manufacturing_TMC+Position+Statement_Final.pdf

7. **TMC's position on biodegradability in the context of fibre fragmentation**, The Microfibre Consortium, https://static1.squarespace.com/static/5aaba1998f513028aeec604c/t/61e002c53fed1c54b171cd85/1642070725693/TMC_Biodegradability_TMC+Position+Statement_FINAL+.pdf
8. **Fixing Fashion: clothing consumption and sustainability**, House of Commons Environmental Audit Committee, **https://publications.parliament.uk/pa/cm201719/cmselect/cmenvaud/1952/1952.pdf**

8.3 UKRI-funded research

AHRC

1. AH/V01286X/1 **Fashion Fictions: imagining sustainable fashion worlds (total funding value: £202,044)**, Nottingham Trent University
2. 2278267 **Home clothes construction in the context of sustainable fashion: design strategies for promoting the development and application of basic sewing skill (total funding value: £65,327)**, Nottingham Trent University
3. AH/V005510/1 **Sustainable Materials in the Creative Industries (total funding value: £119,638)**, Royal College of Art
4. AH/T011483/1 **Augmented Fashion: Immersive Interactions For Sustainable Heritage In Fashion And Textiles (total funding value: £410,374)**, The Robert Gordon University
5. AH/J002666/1 **Laser Enhanced Biotechnology for Textile Design: Three-Dimensional, Colour and Surface Patterning (total funding value: £361,743)**, De Montfort University
6. AH/S002812/1 **Future Fashion Factory — Digitally Enabled Design & Manufacture of Designer Products for Circular Economies (total funding value: £5,601,219)**, Creative Industries Clusters Programme (CICP), funded by UK Industrial Strategy Challenge Fund. University of Leeds
7. AH/R000123/1 **Designing a Sensibility for Sustainable Clothing (total funding value: £361,743)**, University of Exeter
8. AH/T006412/1 **Bioinspired textiles: an investigation into biomimetic principles and their application to sustainable textile design and making processes (total funding value: £200,920)**, University of the Arts London
9. AH/E507964/1 **Considerate Design for Personalised Fashion Products (total funding value: £231,189)**, University of the Arts London
10. AH/N504312/1 **FIRE.Digital: Digital Research Platform for Collaborative Fashion Innovation (total funding value: £80,127)**, University of the Arts London
11. AH/R006768/1 **Rethinking Fashion Design Entrepreneurship: Fostering Sustainable Practices (total funding value: £451,685)**, University of the Arts London
12. AH/S002804/1 **The Business of Fashion, Textiles and Technology (total funding value: £5,644,115)**, Creative Industries Clusters Programme (CICP), funded by UK Industrial Strategy Challenge Fund. University of the Arts London
13. AH/W006936/1 **Cotton's Hidden Voices: Stories from the makers of your clothes (total funding value: £129,987)**, University of Leeds

14. AH/R007497/1 **Stitching Together (total funding value: £24,141)**, Arts University Bournemouth

NERC

15. NE/T00665X/1 **Understanding UK airborne microplastic pollution: sources, pathways and fate (total funding value: £20,261)**, UK Ctr for Ecology & Hydrology
16. NE/T007605/1 **Understanding UK airborne microplastic pollution: sources, pathways and fate (total funding value: £361,743)**, Imperial College London
17. NE/S003975/1 **MINIMISE: Current and Future Effects of Microplastics (total funding value: £723,950)**, University of Exeter
18. NE/P011217/1 **SW Partnership for Environment and Economic Prosperity (SWEEP) (total funding value: £4,118,113)**, University of Exeter

BBSRC

19. BB/T017023/1 **Bio-Manufacturing textiles from waste (total funding value: £628,991)**, University of York
20. BB/V012584/1 **Homes under the microscope: Citizen-led characterisation of airborne microplastic sources (HOME Co-LAb) (total funding value: £289,658)**, University of the West of England

EPSRC

21. EP/S025529/1 **Exeter Multidisciplinary Plastics Research Hub (total funding value: £1,009,856)**, University of Exeter
22. EP/S025456/1 **Holistic integration of technology, design and policy for a greener plastic future (total funding value: £1,027,952)**, Imperial College London
23. EP/S025308/1 **UKRI Circular Economy Approaches to Eliminate Plastic Waste (total funding value: £1,035,067)**, University of Cambridge
24. EP/S025278/1 **Plastics: Redefining Single-Use (total funding value: £1,035,896)**, University of Sheffield
25. 2625614 **Technology as a driver towards slow and sustainable fashion (total funding value: £65,327)**, (PhD studentship), University of Manchester
26. EP/T024542/1 **STOP fibrous microplastic pollution from textiles by elucidating fibre damage and manufacturing novel textiles (total funding value £780,729)**, University of Leeds
27. EP/V042289/1 **Consumer Experience (CX) Digital Tools for Dematerialisation for the Circular Economy (total funding value: £361,743)**, Royal College of Art
28. EP/V011766/1 **UKRI Interdisciplinary Circular Economy Centre for Textiles: Circular Bioeconomy for Textile Materials (total funding value: £4,436,877)**, Royal College of Art
29. EP/S025200/1 **RE3 — Rethinking Resources and Recycling (total funding value: £826,551)**, University of Manchester
30. 1949688 **Enzyme driven performance enhancement of laundry detergents: reducing the associated environmental burden (total funding value: £65,327)**, (PhD studentship), Newcastle University
31. 1655387 **Understanding and controlling dye transfer in the laundry**

process (total funding value: £65,327), (PhD studentship), University of Leeds

32. EP/L017679/1 **Manufacturing of High-Performance Cellulose Fibres to Replace Glass Fibres & Carbon Fibre Precursors (total funding value: £2,060,466)**, University of Bristol
33. EP/R025983/1 **Design and green manufacturing of functional nanomaterials (total funding value: £1,011,132)**, University of Sheffield
34. EP/V052306/1 **Manufacturing solar fabrics by electronic dyeing of textiles with 2D heterostructures (total funding value: £253,042)**, University of Exeter
35. 2417223 **Catalytic chemical degradation of mixed synthetic textiles (total funding value: £65,327)**, (PhD studentship), Cardiff University
36. 2440160 **Synergy between microplastic and sediments within the aquatic system**, (PhD studentship), Cardiff University
37. EP/S025529/1 **Exeter Multidisciplinary Plastics Research hub: ExeMPLaR (total funding value: £1,009,856)**, (2018-2020), University of Exeter
38. EP/G043140/1 PROSPEcT **Ecotoxicology test protocols for representative nanomaterials in support of the OECD sponsorship programme (total funding value: £477,208)**, University of Exeter (an EPSRC/DEFRA/Industry LINK programme to support nanosafety assessment)

Innovate UK

39. 58923 **The Sustainable Recovery of the Fashion Industry from COVID (total funding value: £74,675)**, ACS Clothing Limited
40. 102764 **Extra-light and sustainable textile wind turbine blade (total funding value: £1,021,267)**, Act Blade Limited
41. 85278 **Delivering next-generation smart clothing: Developing safe, sustainable, smart life jacket (total funding value: £349,282)**, Amphibio Limited
42. 131385 **Development of an innovative, reclaimed textile fibre furniture range (total funding value: £24,759)**, Re-Considered Limited
43. 78073 **Sustainable alternatives for COVID-19 PPE: biodegradable wipes and reusable masks made of pineapple leaf fibre (total funding value: £206,835)**, IUK Sustainable Innovation Fund, UAL, Ananas Anam UK Limited
44. 320188 **Piñatex™, a natural and sustainable alternative to leather (total funding value: £50,000)**, IUK Collaborative R&D, Ananas Anam UK Limited

8.4 European-funded research

1. EU FNR14 Horizon 2020 **HEREWEAR (Empowering Local, Circular and Bio-based Textiles)**, 2020-2024, funded by European Commission (total fund £5.5 million), http://herewear.eu
2. Horizon 2020, 2015-2018, funded by European Commission, **Trash-2-Cash** (total fund £7 million), https://trash2cashproject.eu
3. Mistra Future Fashion 2, **Designing Fast and Slow Materials,**

Products, Systems for the Circular Economy, 2015-2019, funded by the Mistra Foundation (total fund £5 million), http://mistrafuture-fashion.com and https://www.circulardesignspeeds.com
4. CLEANSEA EU FP7, **Towards a Clean, Litter-Free European Marine Environment through Scientific Evidence, Innovative Tools and Good Governance**, 2013-2015, https://cordis.europa.eu/project/id/308370
5. NanoMILE EU FP7, **Engineered nanomaterial mechanisms of interactions with living systems and the environment**, 2013-2016, www.nanomile.eu-vri.eu
6. QualityNano, **European Union-funded infrastructure for nanomaterial safety testing**, 2011-2015, www.qualitynano.eu
7. AMPERA, **European Coordination Action to Foster Prevention and Best Response to Accidental Marine Pollution**, 2007, https://www.cid.csic.es/ampera
8. EU H2020 641942, **RESYNTEX: A new circular economy concept: from textile waste towards chemical and textile industries feedstock**, 2015-2019, funded by European Commission (total fund £9 million), **https://cordis.europa.eu/project/id/641942**

8.5 Industry and third-sector funded research

1. WRAP
https://wrap.org.uk/what-we-do/our-services/grants-and-investments
2. The Circular Future Fund: The Million Pound Challenge
https://www.circularfuturefund.co.uk/about.
3. H&M Foundation: Global Change Award
https://hmfoundation.com/gca/winners/
4. Laudes Foundation (previously C&A Foundation)
https://www.laudesfoundation.org/grants/overview-all
5. IKEA Foundation
https://ikeafoundation.org/grant-dataset/

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(front) A melting glacier, an impact of global warming / (back) Develops technologies for extraction and refining of natural dye colours