BIO colours

SUSTAINABLE STORIES FROM NATURE, LAB AND INDUSTRY

Aalto University

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BioColour
FUTURE'S PALETTE

Photo Hung Jui Tsao

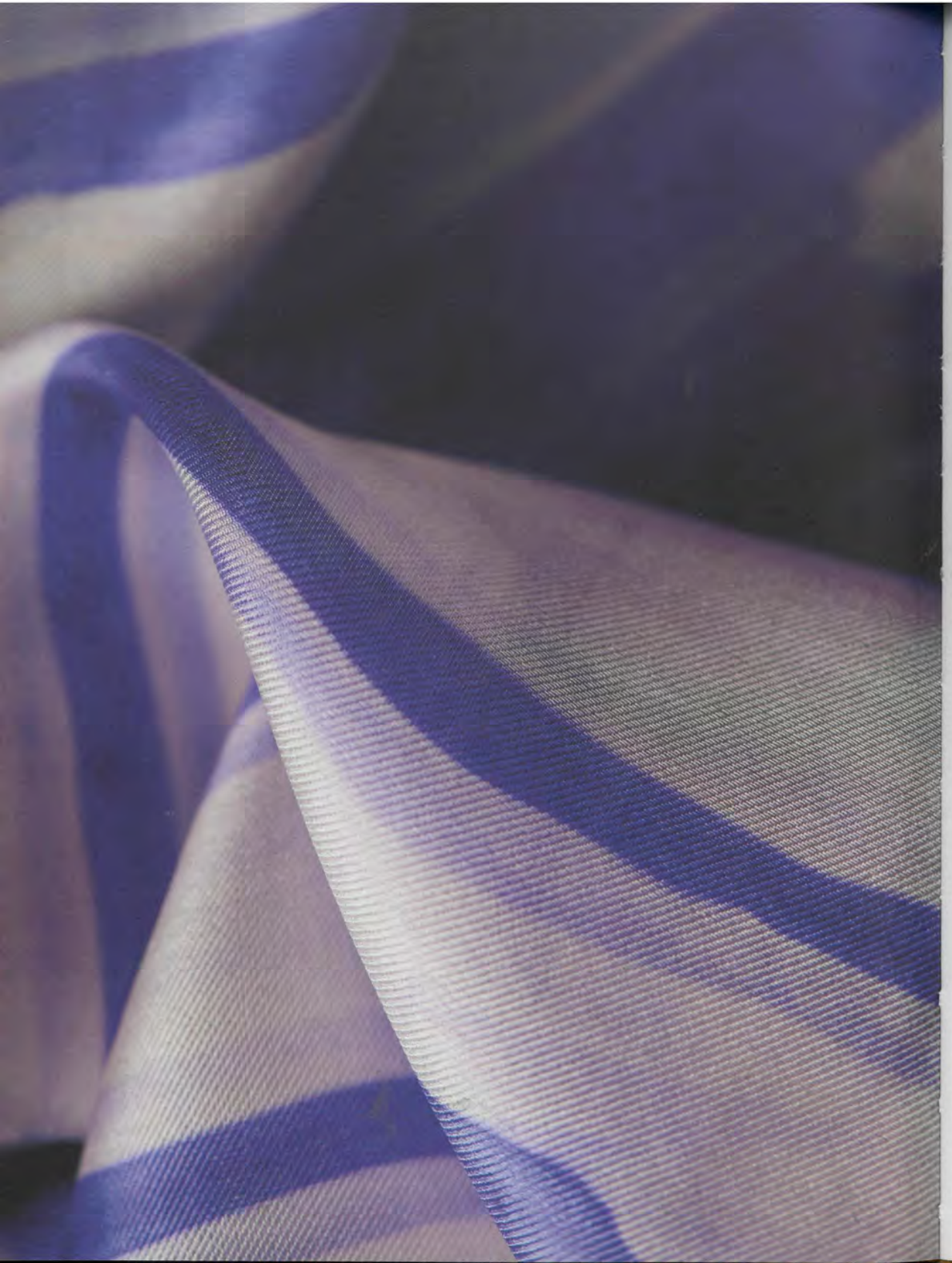
Carole Collet

Towards a life-conducive system reset for textile colouring

ABSTRACT

How can new bio-informed textile colouring practices participate in the process of regenerating our soils, our oceans and our biodiversity? We are on the cusp of a colour revolution in the textile sector. Two key factors are driving this. First the relatively recent emergence of biodesign – the integration of biological tools into the design process – is expanding our approach to colouring textiles. Second, a deeper understanding of the environmental impact of the fashion and textile industry is rapidly stimulating radical innovations. Start-ups are increasingly developing nature-positive colourants made with microbes, algae and biomass waste. Although for millennia, we relied solely on natural ingredients derived from plants, minerals, soil, metals and insects to pattern fabrics, the twentieth century advancement in oil-based chemistry has made prevalent synthetic dyes that are harmful to life. Today, the development of alternative bio-informed dye technologies is opening up a whole new landscape of possibilities. Some of these techniques rely on fermentation, bio-assemblage or bioengineering. Understanding their ecological contribution and limitation is critical in the context of our planetary emergency. This chapter proposes a framework centred on living-system thinking to position bio-colouring processes in relation to life-conducive environmental and ethical principles.

Keywords
biodesign, living systems, life-conducive, microbial colourants, bio-informed strategies



Colouring textiles in a planetary emergency

International scientific evidence shows us that human activities have led to a rapid decline in our planetary health. Today, one million species are at risk of extinction (IPBES, 2019) and we have reached a climate 'code red for humanity' (Guterres, 2021). Intensive farming methods have depleted our soil nutrients (FAO, 2019). Our oceans' life-sustaining capacity is threatened by plastic pollution (UNESCO, 2022). Our rivers and underground water reserves are directly compromised by intensive farming and industrial pollution (Soil Association). The fashion and textile industry is part of this toxic legacy and its detrimental impact on the natural world is well established (Global Fashion Agenda & Boston Consulting Group, 2017, Ellen MacArthur Foundation, 2017). Our modes of textile fabrication are threatening our climate, our biodiversity, and our soils. We urgently need to reverse this decline: we need to transition from a linear, extractive textile economy into a circular bioeconomy that helps restore planetary health. This will require the imagination of new manufacturing systems and exploring new modes of textile colouration will be core to this shift.

Can we imagine viable, scalable alternatives for a post-petrol textile colouring system? Textile colouration today has two main paths: traditional natural dyeing processes, or using synthetic dyes derived from the petroleum industry, a non-renewable resource. The latter is the de-facto standard process used in the global commercial textile industry, whilst natural dyes are only valued as part of small scale, artisanal and local systems. Both processes have a direct impact on the environment. The use of non-renewable synthetic dyes promotes the extraction of oil, which in turn generates large amounts of greenhouse gas emissions, and their disposal in water or soil is hazardous to life (Lellis, B. et al., 2019). Natural dyes are derived from plants, insects and minerals. Contrary to common belief, they can also have a negative impact on our environment when used with traditional metallic mordanting (i.e. chromium, iron, copper salts). These

Automating Violacein, Charlotte Werth
Photo Paul Cochrane for Maison/0

mordants are toxic (Thacker et al., 2022) but in some cases can be replaced by renewable plant-based biomordants (Ashis, 2020; Grande et al., 2023). Plant-based natural dyes can also require large amounts of land to grow. In a context in which climate change is jeopardising our capacity to grow food, producing dye plants on a much larger global scale is not an alternative. Natural dye plants can, however, be grown as part of local holistic regenerative agriculture systems, a form of farming that promotes the restoration of biodiversity and captures carbon (Textile Exchange, 2022). The Fibreshed network promotes this nature-positive approach, as a regional soil-to-soil fashion farming network (Burgess, 2019). Both synthetic and natural dyes require the use of large amounts of water, a commodity at risk in today's context of increased climate-induced draughts. Developing solutions that radically reduce water usage should also be a priority. In this context, we note the development of waterless $C0_2$ dyeing by Dyecoo, a system that uses reclaimed $C0_2$ as a dye carrier instead of water. This technology is based on synthetic dyes, but directly addresses the need to reduce water usage and pollution.

International cooperation negotiated via the United Nations such as the COP 21 Paris Agreement signed in 2015 or the more recent COP 15 Global Biodiversity Framework (2022) drive new regulations and initiatives. In the European Union, a new Digital Product Passport is being prepared as part of the European New Green Deal and will require the environmental impact of every product circulated in the union to be much more transparent. The ZDHC (Zero Discharge Hazardous Chemicals) roadmap for sustainable chemical management within the fashion industry is also driving progress. However, in the context of a critical planetary emergency, beyond optimising existing textile colouring systems, there is also a need to pose new research questions and explore disruptive models. Can we imagine an efficient alternative textile colouring system that benefits the environment instead of depleting life on Earth? What renewable colour processes can be derived from applying bio-circular principles? Can colour obtained from microbial fermentation replace the use of synthetic dyes at scale? Today, we are witnessing the emergence of such alternative bio-circular or bio-informed design research, be it derived from scientific inquiries or led by new design practices. Although not mainstream, nor yet developed on a global scale, they offer a new imaginary for a post-petrol textile colouring process.

The first section of this chapter proposes a framework centred on living-system thinking to position these emergent bio-colouring processes in relation to environmental principles. The following sections discuss a range of design-led projects and examine the potential of these new colouring systems, be they bio-based, bio-assembled or bioengineered.

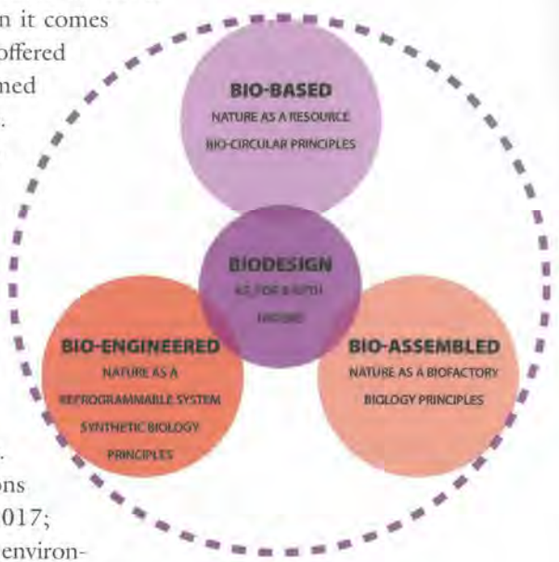
Positioning a taxonomy of bio-informed strategies for textile colouring

Why should we develop bio-informed design and manufacture strategies for textiles? We cannot transition into a nature-positive circular bioeconomy without recalibrating our design practices. Design specifications directly influence material sourcing and manufacturing tools. Nature has been a key inspiration throughout human cultures, as is evidenced in our craft and design history. The concept of the circular economy derives from biomimicry, the emulation and adoption of nature's strategies in human systems (Biomimicry Institute, 2020) and it coincides with the emergence of biodesign, defined as the integration of biological tools and organisms into the design process (Myers, 2012). Biodesign is actioned in both the design and scientific fields and has radically transformed our approach to designing with and for the natural world. In addition to inspiration and imitation, biodesign learns from biological protocols to drive new inquiries into sustainable practices. In the field of textiles, this applies to the development of new bio-informed materials as well as to alternative colour technologies.

The biological world has evolved to function at ambient temperatures, using local resources for energy and nutrients without generating harmful toxic waste (Benyus, 1997). Living systems are by default life conducive: they operate in dynamic, complex and interconnected networks in which the waste of one species becomes the nutrient of others. Learning how to biofabricate as nature does is therefore essential if we are to shift away from our current extractive, linear and oil-centric economy. However, as the field of biodesign and biofabrication expands, diverse practices and narratives are evolving in which the prefix 'bio' is often used as a signifier of sustainability. We need to clearly distinguish the meaning behind the use of terminologies

such as bio-based, bio-informed, bio-integrated, bio-assembled, biofabricated or bioengineered. 'It is not safe to assume that bio is better' (Biofabricate, 2020, p. 5). In the same way, the term 'natural' does not mean ecological: qualifying a material or a pigment with the adjective 'bio' does not imply that it is environmentally positive at scale. Cotton is a good example. Cotton grown in conventional intensive agriculture leads to serious environmental damage: water pollution, CO_2 emissions, high-level use of chemical fertilisers, soil depletion, and biodiversity loss (Textile Exchange, 2018). Cotton is a natural plant that captures carbon as it grows and contributes to its ecosystem when in its native wild environment. Once exploited in monoculture, human-engineered systems, its production becomes toxic: natural does not necessarily mean sustainable. Equally, a 'bio' material or pigment may stem from toxic intensive agriculture, contain limited amounts of biomass or even be a mix of petro-chemicals and bio-based ingredients (Biofabricate, 2020). In addition, some biofabrication processes include genetic engineering, often referenced as a proprietary biotechnology. This lack of transparency and mixed use of terminologies can lead to confusion when it comes to identifying the ecological advantage offered by the adoption of biologically-informed processes in design and biomanufacture.

We need to ensure that we do not simply replicate our extractive approach to the natural world with these new 'bio' narratives and toolsets. Instead we must truly transform our ways of making and transition into a life-conducive circular, regenerative textile economy. Therefore, we need to frame these emergent practices using a critical environmental lens. Cross-referencing existing classifications (Biofabricate, 2020; Camere et al., 2017; Collet 2017; 2021) with life-conducive environmental criteria, figure 1 proposes a taxonomy of interactions with living systems in three parts to articulate the key thresholds across bio-informed approaches in biodesign practice.



1 Bio-informed strategies for design: a taxonomy of interactions with living systems.
Carole Collet 2023

Strategy 1: Designing bio-based materials (see examples in Section 3):

In this framework, the design of bio-based materials entails the adoption of bio-circular principles. By promoting the uptake of biomass waste as a new source for material or pigment production, we remove the need to extract virgin resources, i.e. living space for Nature to recover (Ellen MacArthur Foundation b). This design and fabrication approach uses inert biomass from the leftovers of agricultural systems to create biodegradable and compostable material solutions. In today's linear economy, the management of waste is guided by cost and convenience, not by the laws of nutritious decomposition in nature. In some parts of the world, agricultural waste is burnt (Uma et al., 2022), leading to CO_2 emissions and air pollution, and untreated textile wastewater is released directly into rivers (Athira, 2018). Embracing the concept of biodegradability and designing with and for decomposition should be central to the next generation of bio-based materials (Biomimicry Institute, 2020). However, two main environmental challenges should be considered. This bio-based material design approach should rely on regional and local waste streams, and not promote the global energy-hungry circulation of materials before transformation. Sourcing biomass waste from organic farming systems should also be a priority to support farming models that work in harmony with nature.

Strategy 2: Designing bio-assembled materials (see examples in Section 4):

In contrast to the bio-based approach above, bio-assembled materials harness the active metabolic function of organisms to directly grow materials. They rely on living micro-organisms such as algae, microbes, or mycelium to function as biofactories in closed environments. These organisms naturally generate materials or pigments in their endemic wild ecosystems, but here, their biological capacity is optimised in controlled nutrient baths to be harvested at scale. Using fermentation techniques or cellular agriculture, we can create the relevant parameters for these organisms to live in optimum conditions, by carefully monitoring their temperature, humidity and nutrient levels to enable their best performance. Different methods can be used with different organisms, but they all entail the destruction of the living microorganisms

Bio-informed strategies for the circular bioeconomy	Principles	Environmental benefits	Environmental challenges
1 – Designing bio-based materials Biomass waste as a renewable circular resource	Bio-circular: using biomass waste as a starting point	– Renewable – Biodegradable – Compostable – Reduced need for raw virgin materials/leaves space for nature to recover – Promotes local regional upcycling of biomass waste	– This works for local/regional economies – but is questionable if biomass waste has to travel long distances (CO_2 emissions) – Should not support intensive farming systems by creating value streams for their toxic waste. – Unclear 'bio' terminology: need more transparency and legislation related to actual bio-based content – Knowledge gap: need further research to develop materials that match current industry quality standards.
2 – Designing bio-assembled materials Nature as a biofactory	Biology: relying on living metabolic self-assembly principles to grow materials	– Works at low or ambient temperature in the growing phase – Renewable – Biodegradable – Leftover biofabrication waste can be reused in composting schemes – Promotes the reduction of traditional land use for material production – Growing in controlled environment removes risk of climate-related crop failure	– Requires energy for sterilising feedstock and containers – Feedstock needs to be sourced from organic origins – Limited life-cycle analysis data available – Knowledge gap: need further research to develop materials that match current industry quality standards.
3 – Designing bioengineered materials Nature as a reprogrammable system	Synthetic biology: fine-tuning existing biological functions with genetic engineering to improve and expand biological fabrication capacity	– Works at low or ambient temperatures in the growing phase – Biodegradable – Renewable – Promotes the reduction of traditional land use for material production – Growing in controlled environment removes risk of climate-related crop failure	– Must operate within ethical guidelines – Requires energy for sterilisation of feedstock and containers – Use of GM: Must operate in closed-loop environment in manufacture stage to avoid contamination. – Feedstock needs to be sourced from organic origins – Limited life-cycle analysis data available – Knowledge gap: need further research to develop materials that match current industry quality standards.

in the final stages, (via heat or sterilisation processes) to render the harvested material biologically inert. Using biodesign, we can radically alter creative practice, with the notion of working with dynamic living systems as opposed to inanimate matter. 'Designers are now able to expand their roles from scripting the form-shaping of existing inanimate materials, to creating and growing new biological materialities' (Collet, 2017, p. 25), they can design, as, for and with Nature.

Strategy 3: Designing bioengineered materials (see examples in Section 5):

This biodesign strategy relies on biological assemblage protocols, but also involves the use of genetic manipulation designed to optimise or increase the natural biofabrication capacity of existing microorganisms. Using synthetic biology tools, we can reprogram their metabolic function and tune their performance with precision. This biotechnology needs to be applied in closed-loop systems to prevent any contamination and must operate within strict ethical guidelines. The world of bioengineered materials is rapidly expanding and opens up radical and disruptive possibilities that can fundamentally reshape our relationship with the natural world. We need to cross-examine these possibilities in the context of ethical and just future systems (World Economic Forum & Faber Futures, 2022).

Both strategies 2 and 3 relate to biofabrication, which uses organisms as living biofactories to create materials. Both rely on feedstock, such as sugar, to nourish the selected microorganisms. The provenance of these feedstocks is one of the key challenges in upscaling biofabricated materials and pigments. Here again, we need to prioritise sources from organic and/or waste streams so as not to add value to the leftovers from intensive toxic agricultural models.

The table on the left highlights the key principles of each strategy associated with environmental benefits and challenges. These bio-informed material strategies are recent, and their availability on a commercial scale is limited. Their life-cycle analysis is also limited, and we need to continue monitoring their performance to ensure that their environmental benefits are maintained when produced at scale.

In this section, we have discussed how working with living systems principles can help us transition towards a life-conducive, bio-circular textile economy. We have posited a framework that

situates a taxonomy of bio-informed strategies in relation to environmental benefits and challenges. In the following sections, we discuss how biodesign textile colouring practices are beginning to reshape the sector, be this at the proof-of-concept stage or on a commercial scale.

Bio-based approaches to colour

In this section, we review a range of creative textile propositions as well as new dye technologies that rely on biomass waste as a primary resource to produce colour. These circular initiatives offer a range of inquiries into bio-based colouring other than ancestral natural dye techniques and thus increase their potential.

Colour/Matter, a design research studio led by Rebecca Hoyes and Jo Pierce at Central Saint Martins UAL is dedicated to exploring alternative print concepts for textile colouring. Their project *New Natural 02* (Figure 2) examines the use of undervalued and overlooked food waste as a resource for natural dyes and asks: Can food waste increase the use of bio-based colour?

For this collection, they developed original dye recipes that exclusively use food waste for both dye and print techniques. Interest in using waste streams from the food industry as a resource to produce new materials and extract colour pigments is growing. In 2019, Kaiku, a start-up founded by Nicole Stjernsward developed a process of turning agricultural waste from avocado, pomegranate and onions into powdered textile pigments. Dye manufacturer Archroma has developed Earthcolors®, a range of commercial GOTS-certified (Global Organic Textile Standard) textile pigments made from agricultural waste such as nutshells, leaves, and herbal residues. Wasting food entails wasting large amounts of energy, water and labour required for its production. 'Globally, around 14 percent of food produced is lost between harvest and retail, while an estimated 17 percent of total global food production is wasted' (United Nations, 2022). This is no negligeable amount and represents a potential alternative circular source for pigment production. However, the colour range obtained from food waste is fairly limited (pastel pink and green, orange, brown, purple and greys) and is not a realistic alternative to the full colour palette achievable with synthetic dyes.

In a similar approach, Living Ink, a bioscience research company based in the USA produces Algae Black™ on a commercial scale,

a carbon-negative textile ink. Using the leftover biomass of algae-farmed food colouring production from a neighbouring company (Figure 3), they have developed a unique process to manufacture an OEKO-TEX certified water-based ink for printed textiles. Algae grow rapidly and capture carbon as a source of energy, thus providing a raw material that contributes to reducing our carbon footprint.

Algae waste stream from the food and cosmetic industries are also the primary resource claimed by Zeefier, a natural seaweed textile dye brand launched by Dutch designer Nienke Hoogvliet, in 2021. After nearly a decade of design-led research into the use of algae, Hoogvliet established key protocols to repurpose algae into textile dyes.

Food waste can also play the role of a catalyst to help clean up synthetic dye waste streams. Excessories (Figure 4), a project developed by designer Cassie Quinn, started from the ambition to explore the issue of textile dye wastewater using biodesign tools. Legislation differs from country to country, and the release of synthetic dye

2 *New Natural 02* collection, by Colour/Matter studio, 2019. *Photo Atton Conrad*

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wastewater into rivers is still allowed in some parts of the world with varying permissible limits, even though these dyes contain non-biodegradable pollutants that are harmful to life (Castillo-Suárez et al., 2023). As biological, physicochemical, and advanced oxidation processes can be used to remove such toxic pollutants from synthetic dye effluents, Quinn wanted to explore the recovery of coloured particles as a means to create a new bio-based material.

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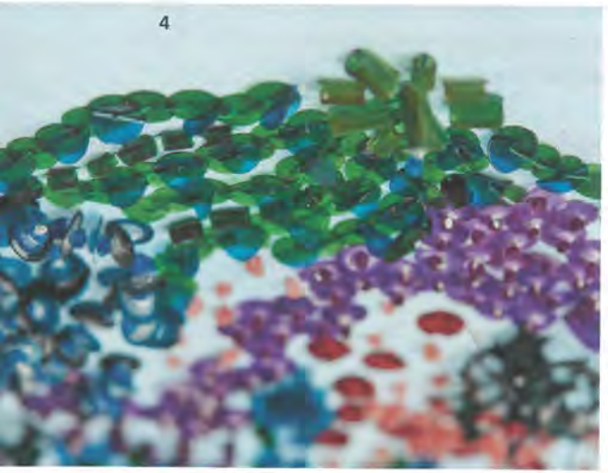

3 Algae production for food colouring.
Photography courtesy of Earthrise Nutritionals

4 Excessories, by Cassie Quinn, 2020, part of a collaborative Maison/0 project with LVMH and the MA Biodesign course at Central Saint Martins UAL.
Photo Paul Cochrane

The project was initiated by Maison/0 as a collaboration between the environment team at the luxury group LVMH and the MA Biodesign course at Central Saint Martins UAL. In the quest for a system reset and the transition towards a fully circular bioeconomy, the project explored the potential of biodesign for future luxury products. By developing a unique bio-based recipe using ingredients derived from food waste, Quinn successfully developed a technique that can clean textile dye wastewater. The process results in a leftover material from which she has produced sequins as an alternative to plastic sequins. The colour of the material is the colour of the wastewater used at the start of the process, which potentially enables a full spectrum of colours.

In this section, we have explored a range of projects that activate carbon capture and circular textile colouring systems. These examples showcase diverse inquiries into bio-based processes, some are still at the prototype level, others are commercially available. Although they do not individually address the scale of the issues linked to textile colouration, they increase and diversify our current options. Reusing waste is core to our transition into a circular textile industry and these projects demonstrate that a new roadmap is possible. However, we also need to ensure that by creating new dye processes we do not incite or sustain the production of waste, but simply offer propositions relevant to unavoidable forms of waste. It would also be useful to source biowaste from organic origins as opposed to creating added income for intensive farming food systems.

Bio-assembled colour

Learning from the natural biological world is key to biodesign. In this section, we focus on examining the development of alternative colouring processes that rely on working with living organisms to produce pigments, be they extracted from organisms or directly grown onto cloth. One of the key principles of biology is self-assembly: cells directed by their DNA codes will grow, evolve and self-assemble in a range of active structures and behaviours. In the natural world, many organisms rely on local ingredients such as solar energy, rainwater and macronutrients to produce colour at ambient temperatures without generating toxic byproducts. We can learn from these biofabrication principles. Some bacteria, algae and fungi are indeed able to produce

pigments using their intrinsic biological capacity. Working with bio-assembled colouring processes is now a realistic emergent form of textile colouring, driven by both biodesigners and scientists alike.

More than a decade ago, pioneer designer Natsai Audrey Chieza, founder of Faber Futures, prototyped textile printing with bacteria in collaboration with Professor John Ward at UCL. The Coelicolor project has since been further developed as an inquiry into design-driven protocol for bacterial printing. Today, we are witnessing the development of promising new microbial dye technologies, now reaching commercial scale. Microbial research has shown clear environmental benefits, including biodegradability and significant water-saving in comparison to synthetic dyes (https://faberfutures.com/projects/project-coelicolor/). Bacterial colours also work across fibre types (cellulose, keratin or synthetic) without needing toxic mordanting.

For textile designers, the application of bacterial colour onto cloth is more than an environmentally beneficial technical process; it is also a new platform for creativity. Every new technique calls for imaginative applications. This was the focus of Charlotte Werth's *Automating Violacein* produced for her design residency at Maison/0 (Figure 5).

With the bacteria printing machine she developed for her MA Material Futures graduation project at Central Saint Martins UAL, Werth has further explored the potential of this automated technique to develop a range of printed textiles using *Janthinobacterium lividum*, a wild soil-dwelling bacterium. By experimenting with folding, pleating, resist techniques and multiple dye run throughs, Charlotte has created a variety of patterns. The challenge for the designer is to orchestrate a life-support nutrient system for bacterial growth, whilst at the same time engineering a patterning process by controlling the areas of the fabrics exposed to the activity of live organisms.

In addition to bacteria, fungi can also be used as a cellular pigment-producing organism, as demonstrated by Liene Kazaka in her Myco Colour project, developed for her MA Material Futures graduation thesis at Central Saint Martins, in 2021. Using *Chlorociboria aeruginascens*, a green elfcup fungus, to release a turquoise pigment directly onto fabric as it grows, Kazala eliminates the need for chemicals by relying on the active biological properties of this fungus to fix pigment into fibre. According to her research, the

5 Automating Violacein by Charlotte Werth, 2023. A Designer in Residence Maison/0 project at Central Saint Martins UAL.
Photo Paul Cochrane

pigment produced by this mushroom has shown equal colour fastness to commercial dyes (https://lienekazaka.com). Although this project is a proof of concept, it has established new knowledge in the field of textile colouring and demonstrates the potential of exploring further principles of living colours found in nature.

The world of fungi also informed Julia Jueckstock's Hyphea Hues project, part of the collaborative Maison/0 project mentioned above, in 2020. Referencing the culinary recipe of grain fermentation traditional in Japan, China and Korea, Jueckstock used a red yeast fermentation process to cultivate a living pigment for textiles. Using waste from a local distillery as feedstock, she developed an original yeast-based recipe to either dye fabric in live fermentation batches, or to produce a print paste by extracting the red pigment. Figure 6 shows a scarf first dyed with live red yeast, then screen printed with a yeast paste.

Although the projects above exemplify the potential of working with living organisms to develop bio-assembled protocols for textile colouring, they remain limited in their industrial applications to date. Bacterial colours derived from natural organisms found in nature, also called 'wild type', offer real ecological advantages: they remove the need for the mordanting used in traditional natural dye recipes to fix pigment into fibres. They also work across fibre types (cellulose, keratin and synthetics) and require less water than both natural and synthetic dyes. They are biodegradable and their nutrients can also be derived from waste sugar feedstocks. However, their colour and light fastness is limited, and this presents a real barrier to achieving an industry standard for large-scale applications. The colour range of wild type is also very limited bacteria (mainly purple-pink and grey hues). These limitations can be addressed by using biotechnology and genetic engineering, examples which we discuss in the next section. Using live fungi and yeast to dye textiles is less developed than bacterial dyes but represents yet another path to explore further.

Whilst there is an established body of literature on the use of natural dyes, there is a knowledge gap concerning the use of organisms as living cellular pigment factories. Yet we are very experienced in working with organisms such as yeast for the production of beer, wine, cheese and other culinary traditions. Perhaps we can explore the transferability of such knowledge to establish a new kind of textile colouring process derived from natural fermentation protocols. This

approach to bio-assembled colouring with wild type microorganisms, in which the production of colour is directly controlled by cell factories, is still at a nascent stage and requires further research to establish its full potential in terms of scalability.

Bioengineered colour

A growing number of designers are experimenting with the creative potential of wild type bacterial dyes, but above, we have established their limitations in terms of industry performance and colour range. In parallel to biodesign research, an increasing number of start-ups led by scientific research are dedicated to using biotechnology to improve the performance of microorganisms for textile colouring. Their mission is to develop biodegradable dyes that can replace harmful non-renewable synthetic dyes and be competitive in terms of quality performance and price range. A leading company in this field is Colorifix in the United Kingdom. Using

6 Hyphea Hues by Julia Jueckstock 2020, part of a collaborative Maison/0 project with LVMH and the MA Biodesign course at Central Saint Martins UAL. *Photo Paul Cochrane*

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DNA sequencing and digital tools (not real specimens), Colorifix is able to identify colour-triggering genes in nature and translate them into microorganisms to produce an extended colour range. In a recent Life Cycle Analysis impact assessment, Colorifix established that their dyeing process uses 77% less water, 80% less chemicals, and a 31% reduction of global warming contribution compared to conventional synthetic dyeing processes (Colorifix, 2022). Their microorganisms are bioengineered, grown in bioreactors, then destroyed in a closed loop extraction process. What remains is effectively a brewed natural pigment that can be used in existing dye manufacturing systems. Colorifix is in the process of developing this technology at scale and is actively collaborating with design brands and textile manufacturing such as Acatel (Figure 7) to retrofit the use of microbial dyes into existing manufacturing

7 Microbial printed textiles by Acatel using Colorifix dyes.
Image courtesy of Colorifix and Acatel

8 This is GMO by Jen Keane, founder of Modern Synthesis, in collaboration with scientist Marcus Walker.
Photo Ed Tritton

systems. Colorifix has also recently launched a collaborative doctoral research project in collaboration with the Living Systems Lab at central Saint Martins with designer Ruth Llyod to develop a new framework for microbial textile printing and to accelerate the adoption of biofabricated colours in the global textile industry.

Pili in France has also industrialised the production of biofabricated coloured pigments and is a proactive leader in the decarbonisation of the textile industry due to its use of efficient, scalable biological solutions. Huue in the USA is focusing on the development of a biosynthetic indigo dye that could replace synthetic indigo, thus potentially radically reducing the environmental impact of the denim industry.

Bioengineered colour production presents a paradox. On the one hand these technologies use bioengineered organisms, but on the other hand, the resulting process is a form of natural biodegradable pigment that radically reduces the use of water and energy. These engineered microorganisms also allow us to bypass the use of heavy metals and harmful chemicals normally required to fix colour onto fibre. Biotechnology enables us to tune existing biological performance and to adapt them to a fermentation process akin to brewing for large-scale production. As these alternative renewable biofabricated colour technologies develop into industrialised systems, we need to remain vigilant in terms of ethical practice. Ongoing environmental audits will also be critical to further demonstrate their benefits, but so far they have proven to outperform conventional synthetic dyes in terms of environmental criteria with a reduced impact on water, and less chemicals and CO_2 emissions.

Traditionally, we manufacture textile materials before we colour them. With biofabrication tools we can also converge these two steps into one. *This is GMO*, a black bacterial cellulose shoe prototype (Figure 8) is a project led by Jen Keane, founder of Modern Synthesis, in collaboration with scientist Marcus Walker.

The colouration of materials in situ during growth is a regular occurrence in nature. This principle was applied in the production of the upper part of the shoe, and black melanin pigment growth was engineered into bacterial cellulose production (Walker et al., 2023). Bacterial cellulose is a natural biomaterial produced by a range of bacteria and is cream coloured in its natural state. *This is GMO* demonstrates the potential of biofabricating both textile

material and colour at the same time and opens the door to radical, disruptive innovations for the future of the biotextile industry.

Above, we have shown that bioengineered colour technologies are able to leverage the colour production of natural living organisms to outperform petro-chemical colouring processes in terms of environmental criteria. They are renewable, biodegradable, and considerably reduce the amount of water and chemicals needed for the colouring process. They can also potentially enable us to converge material and colour production into one single biofabrication stage. However, the range of colours these processes can produce is still limited and so far cannot compete with the spectrum provided by synthetic dyes. Bioengineered colour production is also a very new industry with limited datasets in terms of Life Cycle Analysis. We must continue to monitor the performance of bioengineered colours once implemented on an industrial scale to ensure that they fulfil their original mission, that of shifting from a harmful oil-based to a life-conducive textile colouring system.

Rewilding textiles: a post-petrol colour palette

In the sections above, we explored three different bio-informed colour strategies: bio-based, bio-assembled and bioengineered. Although these can all offer environmental benefits; their respective colour capacity is limited in comparison to cost-effective, versatile synthetic dyes. The Rewilding Textiles project set out to explore the intersection of these colouring processes and to establish their potential when combined (Maison/0, 2022).

Recognition that regenerative textile farming can help the fashion and textile industry meet its climate and biodiversity objectives is growing (Textile Exchange, 2022). Fibres grown in regenerative agriculture contribute to drawdown carbon and to restoring biodiversity, but once absorbed in the global textile manufacturing system, they are treated with conventional synthetic dyes. The project

9 Textile collection from the Rewilding Textiles project by Maison/0 Central Saint Martins UAL, 2022.
Photo Hung Jui Tsao

asks: Can we align a colouring textile system with these regenerative fibres? (Maison/0 2022: 9)

The final output consists of a series of textile collections and a publication that contextualises regenerative textile design practice from fibre to colour. For the project, new dye and print protocols were developed to combine the use of microbial dyes (both wild type and bioengineered), algae, food waste and biomordants. Figure 9 shows a twelve-colour set of textile samples screen-printed on regenerative wool. Some of the colours come from one origin (for instance algae), others are achieved by combining two sources (such as algae and bacterial dyes). One of the key challenges was to gather the relevant expertise to work across these different bio-informed colour recipes. A team of six designers with diverse textile dye knowledge and the support of biologists and a natural dye expert was required to achieve the range of expanded colour palettes. All the colours of the spectrum were successfully produced when bio-based, bio-assembled and bioengineered dyes were combined, except fluorescent colours. Rewilding Textiles is the first prototype collection entirely produced using regenerative fibres and printed using a mix of bio-informed colour processes. This proof of concept demonstrates the need to further develop these emerging colour technologies at scale, so as to complement the current progress achieved in regenerative textile fibre production.

Conclusion

In this chapter we have established that in the context of a planetary emergency, the textile industry needs to transition towards a bio circular and regenerative model. This entails considering post-petrol colouring systems and breaking away from using non-renewable, polluting, synthetic dyes. Learning from how living systems operate in the natural world, at ambient temperatures with local nutrients and without the release of toxic byproducts, we can envisage new bio-informed dye technologies beyond the use of natural dyes. Natural dyes do not offer a realistic alternative to synthetic dyes at scale but are beneficial when grown in regional regenerative agriculture, using biomordants as opposed to traditional toxic heavy metals. The circular bioeconomy provides a new context for re-imagining a bio-informed textile landscape and coincides with the emergence of biodesign practice and the integration of biological protocols in the design process.

As the field of biodesign and biofabrication is expanding rapidly, the flurry of 'bio'-related terminologies can lead to assumptions and confusion. We need to position bio-informed design and material strategies in relation to life-conducive environmental and ethical criteria. This chapter posits such a framework and defines a taxonomy of interactions with living systems in three parts to articulate key thresholds across bio-informed practices. It examined a range of new, nature-positive dyes and colour projects in relation to the proposed framework (bio-based, bio-assembled or bioengineered) and their respective colour range capacity. As they stand, bio-informed colour innovations offer a limited colour palette, but the option to combine dyes from mixed bio-origins could expand the colour range to a full spectrum, except for fluorescent tones. Bio-informed colour research is conducted via different streams: it can stem from design-led inquiries, scientific research or start-ups, which are beginning to scale up on a commercial scale. Although key knowledge gaps need to be overcome before bio-informed dye technology can truly compete with synthetic dyes in terms of cost and versatility, there is clear evidence that biocolours can outperform chemical dyes in terms of environmental benefits. We have seven years left to meet both our climate and biodiversity deadlines, so it is imperative that the development of these nascent bio-informed dye technologies is accelerated. The textile industry we know today was at the heart of the industrial revolution in the 18th and 19th centuries. The textile sector can once again lead the biorevolution and offer a system reset to revitalise the natural world with life-conducive fibre and colour systems. This will take more collaboration across sectors than ever before, but the promise of scalable nature-positive colour dye technologies is real.

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