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Future fashion, biotechnology and the living world: microbial cell factories and forming new 'oddkins'

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Bios

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Alice Payne: Alice Payne is an Associate Professor in Fashion in the School of Design, QUT. Her research centres on environmental and social sustainability concerns throughout textile and apparel industry supply chains. Alice has examined the cultural and material flows of post-consumer textile waste, and design processes of mass-market product developers, independent fashion designers, and social entrepreneurs. She is author of the book *Designing Fashion's Future: Present Practice and Tactics for Sustainable Change* (Bloomsbury 2021).

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As the urgency around the environmental impact of fashion production grows, biotechnologies that engineer microbes and other biological organisms such as plants offer cleaner, greener processes and entirely new products. Bacteria and yeasts may be engineered to colour fabric, generate synthetic fibre precursors or natural fibres such as silks, and produce enzymes used to break down and convert waste. Biotechnology can also present as a continuation of humanity’s mastery over the natural world. This article explores how biotechnology may offer fashion - as both industry and culture - alternative ways of knowing and forming relationships with the natural world, offering a range of propositions for the role of biotechnology in fashion practice. The first theme, ‘taming’, examines how biotechnology offers alternatives that control and reduce environmental impacts within existing industry norms. Taming includes synthetic biology and microbial biotechnology to develop processes for silk and leather alternatives, and the replacement of existing fossil-fuel based fibres with bio-based equivalents. The second theme, ‘rewilding’, focuses on the role biotechnology may play in local, decentralised fashion production existing outside of industry control, within the community. Last, ‘speculating’ shows the role biotechnology may play in imagining and enacting alternative views of the living world in which the human and more-than-human entangle to form new kinships.

Keywords: bacterial cellulose; biotechnology; fashion; kinships; rewilding; synthetic biology; speculating; sustainability; taming

Introduction

Fashion appears to be on the cusp of a biotechnological revolution, one that promises cleaner production processes through manipulation of organisms and biological processes. Although there are long-established examples of biotechnology in fashion and textiles, from selective breeding and genetic modification of cotton to enzymes used to finish textiles, recent industrial biotechnologies include engineering of microbes and other biological organisms, offering greener processes and entirely new products. Bacteria and yeasts may be engineered to colour fabric, produce enzymes to break down and convert waste into usable materials, and generate biochemicals to replace petrochemicals as the feedstock for manufactured fibres. With the development of facile and flexible genome editing technologies such as CRISPR (the topic of the 2020 Nobel Prize for Chemistry) and the means to design and engineer biological systems, synthetic biology (synbio) allows for natural processes to be enhanced still further (Pickar-Oliver and Gersbach, 2019). In all instances, whether traditional or contemporary, these biotechnologies are a means to develop living organisms and natural processes for human ends, and contemporary forms appear to promise a cleaner future for fashion.

The need for less-polluting processes in fashion and textile production has never been more pressing, with the grave ethical and environmental impacts of fashion well-established (e.g., see Niinamaki et al 2019). Yet technologies to clean up the industry do not get to the root causes of fashion's unsustainability (Fletcher 2014), and indeed, new technologies may serve to cement corporate power and further promote overproduction and overconsumption. More fundamentally, biotechnology's manipulation of the living world for human ends could be framed as a continuation of humanity's ongoing exploitation of nature. The posthumanism of Donna Haraway (2016) offers another ontology altogether, revealing humanity to be inherently entwined in multispecies 'kinships', the human in partnership with the more-than-human.

Biotechnology may indeed offer a continuation of the industry's extractive status quo, albeit a cleaner, greener version, and yet it may also be imagined as the human in partnership or even kinship with the living world. In this article, we ask, what is the current state of play for biotechnology in fashion, what futures are suggested, and what do these claims mean both practically and philosophically? We propose that biotechnology can offer fashion – as both industry and culture – diverse ways of knowing and forming relationships with the more-than-human world.

To examine these questions, we examine narratives for the future of fashion and biotechnology through drawing on examples from the present. In the last five years, there has been a large increase in articles and publicity regarding the use of biotechnology in fashion and textiles. We identified fashion business, textile trade publications, industry reports and design press reports on fashion and biotechnology from 2015-2020[1], and gathered examples of start-ups, designers, artists and companies applying biotech to fashion and textiles. Interpreting these, we draw upon our experiences as researchers and practitioners: designers working with biotextiles (Authors 1 and 3) and a scientist specialising in microbial biotechnology (Author 2). We identified categories of biotechnology examples in fashion that enabled us to establish three themes - taming, rewilding and speculating - as narratives for the future of fashion biotechnology. These themes offer three different ways to position biotechnology within the fashion system, and additionally, suggest different modes of multispecies relations.

Biotechnology as human and more-than-human entanglement

Discussions of biotechnology and sustainable fashion must first be framed within a philosophical and political context. Biotechnology, put simply, is the manipulation and engineering of other organisms to make useful products. Humans have been shaping other living beings for human benefit for thousands of years with examples including the domestication of plants and livestock by modifying them through breeding and selection for improved characteristics, and the domestication of yeasts for brewing and baking. In the Neolithic era, people practised fermentation by using bacteria and yeast to make bread, wine, beer, cheese, yoghurt, and soy products. For millennia, genetic manipulation through natural selection has created an evolution of genes and organisms, prior to today's modern form of biotechnology (Belt 2009). However, modern biotechnology evolved through the 20th century and deals with the precise genetic manipulation of organisms, materials, and/or biological agents with enhanced attributes. Modern biotechnology is more powerful and faster than selective breeding and selection, but is yet a continuation of what humans have been doing for millennia.

Philosophically, in Western modernity, there is a longstanding division between human and nature, with 'nature' as a state outside of human culture (Williams 1986). The work of Latour (1993) and others in Science and Technology Studies (STS) dissolves modernity's view of human exceptionalism, and indeed the nature/culture divide, through proposing a 'flat ontology' (Conty 2018) in which human and non-human actors alike exercise agency and form entanglements[2]. Haraway (2015; 2016) describes humanity as living with and comprised of multiple species (think of the bacteria in our gut), in kinship through symbiotic as well as host-pathogen relationships. Haraway's posthumanism offers a way to examine the varied ways the human is sister and collaborator, partner and combatant with other species: the human in continual negotiation with the more-than-human. Humanity can 'make kin' with these species, and the 'oddkins', as Haraway puts it, 'requiring each other in unexpected collaborations and combinations' (2016, ii). The 'oddkins' formed with and through biotechnology, whether bacteria that form new materials or cell factories engineered to become a microbial workforce, are manifestations of human and more-than-human entanglements, and our interconnections are new kinships.

A flat ontology of human and more-than-human entwined offers a way to view biotechnology as a partnership between humanity and the living world, albeit to varying degrees and to varying ends. Politically, the more-than-human can be conceived of as a labouring actor. Gabrys (2013) describes as ‘carbon workers’ the innumerable ocean microorganisms living amongst, interacting with and over long time periods, potentially breaking down the plastic waste. Their labour, ‘intra-actions’ and new ecologies represents a transformed ‘material politics’. Oil, transformed into plastics, is originally formed from the ancient remains of organisms laid down millions of years prior. Genetic modification becomes a finer means to do the modification and manipulation humans have long undertaken. Microbial cell factories harness the workings of the cell to generate products that humans require with high efficiency using biological feedstocks (for example sugars from plants derived from atmospheric carbon dioxide via photosynthesis) or directly from gases using gas-fermenting microorganisms or microalgae through photosynthesis.

These examples make visible the complexity of human and more-than-human interactions, yet they also present a political challenge. As philosopher Lie (2016, 7) poses, if we no longer have a clear conception of naturalness, we become free to ask the dangerous question, ‘what kind of nature do we want’? Asking this question in the Anthropocene, a world shaped by and for (certain) humans, means that humanity has free rein to further exercise dominance over the living world. In her analysis of the synthetic biology community, Bensaude-Vincent (2013, 30) describes synbio’s vision of nature ‘as a field of potentials to be explored for its affordances.’ In this ‘techno-scientific utopia’, synbio can open up ‘a new era of clean and sustainable development based on the systematic exploitation of biological resources’ (Bensuade-Vincent, 2013, 28). The outlook remains implicitly human-centred. As humanities scholar Wodak

(2020, 2) puts it, biotechnology is 'predominantly used for perpetuating so-called human civilisation rather than benefitting the more-than-human world'. While biotechnologies may be viewed as novel entanglements of human and more-than-human interaction, the power and control still rest with the human.

A middle ground, perhaps, lies in the notion of stewardship, in which principles of care for the living world are centred, and the human world is decentred. Environmental ethics purports an ethics beyond the anthropocentric to the biocentric (Liu 2016). Similarly, in writing on fashion design and sustainability, Kate Fletcher (2014) contrasts technocentric design with ecocentric design. Ecocentric positions align with more radical conceptions of sustainability that disrupt the status quo to foster transformative system change, while the technocentric are incremental improvements that serve to improve and sustain the existing industry.

Critiques of biotechnology from the humanities and social sciences position it firmly in the realm of the technocratic as a 'promissory technofix,' instrumentally solving a material problem while ignoring the 'profound inequities of race, gender, and class that have disproportionately fuelled the ecological crisis' (Wodak 2020, 4). Yet, as Wodak observes, there is a shift underway from the 'normative applications' of biotechnology as human-benefitting to biotechnology 'benefitting the more-than-human world' (2020, 7). In weighing up the ethics and politics of biotechnology applied to conservation efforts, Wodak describes the paradox of such interventions for sustainability as being at once 'timely' and 'too late' (2020, 15). How biotechnology may assist in transforming fashion towards sustainability and stewardship, versus an incremental improvement to the existing system, will depend on the mindset and orientation of the designer, company or user implementing it. An ecocentric philosophy of biotechnology in fashion would see the technology in service to the greater goal of care for the living world, not only in response to ecological crisis, but also in response to the systemic injustices that have led to it. We turn now to examine the forms of biotechnology currently occurring in fashion.

Current state of play: Forms of biotechnology in fashion and textiles

Both traditional and modern forms of biotechnology co-exist in fashion and textile production. Currently many applications exist for biotechnology, including in novel fibre and material development, in textile dyeing, in breaking down textile waste, and in textile finishing. We will focus specifically on the development of new materials, including approaches to dyeing. To provide context for these materials, Table 1 presents a classification system for fibres and textiles, adapted and developed from Collet (2016). The table represents a developing order of complexity and technology applied to textile production. The first category, natural fibres, represent the traditional form of biotechnology in which humans domesticated plant and animal fibres such as cotton and wool. In the wild, the cotton boll grows in a wide range of colours from blues to browns to pinks yet has been selectively bred to be white for ease of dyeing.

Table 1. Textile classification system[3]

Natural fibres (agriculture)	Cellulosic (from plants such as cotton, linen from flax, hemp, ramie, nettle etc.) and protein (from animal origin, e.g. wool, silk etc.) fibres.
Regenerated cellulosic fibres (manufacture)	Fibres made from cellulosic plant-based material (such as wood pulp) and then chemically processed. They include rayon and viscose.

Bio-derived natural fibres and fabrics (biofacture)	Bio-derived natural fibres and fabrics and leather alternatives begin with a biological material such as seaweed/algae, bacterial cellulose, or fungal mycelium and create a textile as a final product.
Petroleum-derived synthetic fibres (manufacture)	Fibres made from petroleum derivatives. They include nylon, acrylic, and polyester.
Bio-derived synthetic precursors (biofacture)	Precursor ingredients needed for fibres or fabrics made using biological organisms. For example, biosynthesized indican for indigo (Hsu et al. 2018), biobased paraxylene, a key ingredient for the transformation of petro-based polyester to 100 percent renewable content (Textile Exchange 2020), and chemically identical synthetic fibre precursors (Lee et al. 2019).
Engineered organism-derived fibres and fabrics (biofacture)	Fibres and fabrics made with genetically manipulated organisms. These organisms exhibit enhanced properties that influence the qualities of fabric and production yields. They include spider and bee silks made in engineered bacteria and yeasts. The difference between bio-derived natural and

engineered organism-derived fibres and fabrics are the choice of organism not the final material.

Modern biotechnology methods are being further developed, with cotton seeds genetically modified so that the plant is resistant to the boll worm (Dhivya et al. 2016). Additional contemporary forms of biotechnology are emerging, and the following sections represent different forms occurring in fashion.

Replacement of existing synthetic fibres with biobased equivalents

One of the strongest areas emerging from biotechnology in the textile industry is the replacement of existing synthetic fibres with biobased equivalents such as nylon or elastane precursors made from sugar using engineered microbes. Biobased equivalents or biosynthetic fibres consist of polymers or materials that have been derived from renewable resources instead of non-renewable. In 2020, biotechnology company Genomatica announced it had produced the first renewably-sourced tonne of a key ingredient found in nylon-6 made by microbes using sugar from plants rather than chemicals from oil refining (Genomatica 2020). Every year, more than 5 million tonnes of nylon-6 are produced. Whereas traditional nylon is responsible for 60 million tonnes of greenhouse emissions annually, synthetic bio-based nylon offers an alternative to the environmental consequences of petroleum-based fibres that are made from fossil carbon.

The production of biobased, chemically identical equivalents of synthetic fibres has its pros and cons. For its advantages, the production of biosynthetic fibres reduces the ecological impacts and overreliance of non-renewable resources that current synthetic fibres rely upon. On the contrary, it could be argued that biosynthetic fibres perpetuate the status quo and avoid the dilemma of overproduction. A further consideration is the rise in microplastic pollution from the shedding of fibres from textiles such as polyester and nylon (whether of fossil carbon or biobased origin). Although a feedstock may be from a renewable source, the whole life cycle must be considered including impacts from farming and the production of sugars for fermentation. Nonetheless, these fibres point to the necessary, urgent transition away from non-renewable fossil oil to renewable bio-based feedstocks.

Generating fibres and materials through biotechnology

While the intention might be to create a biobased equivalent of a synthetic fibre, a generation of new fibres has emerged that are inspired by nature or are not like their synthetic counterparts. Fibres that can be deemed superior and stronger than synthetic counterparts such as spider silk are in the process of development. At first, spider silk was primarily compared to its silkworm counterparts (Twilley 2017). Yet, as the research developed and the evolution of spider silk kept improving its textile qualities, spider silk emerged as a promising textile for more than fashion applications – its tensile strength has been said to be five times stronger than steel and tougher than Kevlar (Miceli 2018; Wood-Black 2018). These improved and tailored properties raise interesting possibilities and ideas for the future, as biosynthetic fibres continue to be developed via synthetic biology and utilized in other industries beyond fashion.

Biotechnology also offers opportunities to improve regenerated cellulosic fibres traditionally formed from wood pulp. Australian company Nanollose has developed tree-free rayon manufactured fibres. Comparing to traditional rayon which has unsustainable wood processing practices, their rayon fibres are created through a bacterial cellulose process and seeks to provide eco-friendly alternatives in comparison to traditional cotton and rayon fibres and clothing (Abdulla 2018a). Although currently not at scale, the advantage of these materials is that they can offer a replacement for conventional substrates for regenerated cellulosic fibre manufacture that can integrate into existing textile production processes.

As well as using bacterial cellulose as the feedstock for regenerated cellulosic fibres, new innovative biomaterials that are evolving in popularity can be made directly from bacterial cellulose as well as fungal mycelia. These materials are examples of biotechnology being used to develop substitutes for traditional materials such as leather or faux leathers such as poly-vinyl chloride (PVC). Initial approaches towards material replacements seek to use waste by-products from one industry for the creation of new clothing and accessory textiles and are aligned with the move towards a circular economy. Bacterial cellulose has been made using waste ingredients such as sunflower meal, confectionary waste, palm date, fig, and cotton textile waste. Fungal mycelia can be grown on forestry by-products such as sawdust and leather replacements can be made directly from plant materials such as bananas, cactus, cereal crops, corn, flowers, fruit waste grapes, mulberry tree leaves, pineapples, and teak leaves (Enjoli 2018; Hirsh 2020; Sewell 2015). The advantages here lie in the utilization of low-value agricultural fibres, co-products and wastes as well as in the ethical implications of meat production and the environmental impact of methane emissions from cattle.

There has been an increase in the number of start-up and biomaterial companies using biotechnology and synthetic biology for new materials. These companies include AlgiKnit, AMSilk, Biofabricate, Bolt Threads, Modern Meadow, Malai Biomaterials, and MycoWorks. AlgiKnit concentrates on creating biodegradable yarns and fabrics from algae. AMSilk is dedicated in the development of a biobased silk equivalent for products involving textiles, cosmetics, and medical devices. Bolt Threads is a company focused on material innovation working on various biomaterials such as Mylo mycelium leather and MicroSilk. Modern Meadow is developing Zoa, an alternative leather that is created using the biologically produced collagen protein in the laboratory without having to use animals for leather. Malai Biomaterials creates a biocomposite material using bacterial cellulose and coconut water that is ethically sourced in southern India. MycoWorks is a sustainable start-up that creates apparel and products using fungi. As with the previous examples, these materials offer to substitute existing materials used in fashion using more environmental or more humane production methods.

Use of biotechnology to make dyes

The research regarding the use of biotechnology to make dyes for the textile dyeing process of clothing and garments has also been increasing. In 2018, Colorifix raised US $3 million dollars to scale up its dyeing process using synthetic biology methods (Abdulla 2018b). Through the process of integrating genes encoding enzymes for the synthesis of dye molecules into bacterial cells, they are able to produce a range of colours that are naturally made by organisms such as microbes, plants, and animals. The importance of new approaches to dyeing has resulted in Colorifix building relationships with major partners such as H&M (Ringstrom and McDill 2019). An additional recent example of biological dyes includes US start-up Huue, who are using bacteria to sustainably produce indigo dye for the denim industry via fermentation biotechnology (Russel 2019)[4]. The technology was tested on garments and swatches of fabric to show its potential as a sustainable dyeing system using biotechnology.

Fashion's future: three narratives for fashion and biotechnology

Taming: Biotechnology for a cleaner industry

Taming refers to the use of biotechnology to transform the existing industry to be cleaner and more efficient. The recent 'Design with the Living' symposium, held in London in 2019, posed the question, 'Can designing with living systems be the change we need in the context of today's current environmental and ecological challenges?' proposing the role of biotech as 'designing with and for living systems' (Design Museum 2019). This 'designing with' and 'designing for' the living is the critical dimension, as the promise of many of the technologies described above is to optimise production processes while reducing environmental impact for benefit of human and more-than-human alike.

New partnerships, collaborations, and prototypes are being developed with the materials derived from fashion biotechnology. For instance, in 2017 Adidas and Stella McCartney announced a partnership with Bolt Threads to develop new materials. The Bolt Threads website described the partnership as, 'Combining Stella McCartney's relentless pursuit of sustainable materials with Bolt Threads' proprietary breakthroughs in industrial biotechnology, the partnership represents a step-change for the future of apparel production, and the fashion industry at large' ('Stella McCartney and Bolt Threads Announce…' 2017). The key emphasis for Stella McCartney was producing vegan materials with a lower environmental impact.

In 2020, Bolt Threads announced another partnership for their mycelium-based material, Mylo. This partnership involves a consortium of companies including Adidas, Kering, Lululemon, and Stella McCartney aiming to work together for the development of Mylo. Mylo can be created from ingredients to final products within two weeks, versus the number of years needed to raise livestock in the production of animal leather.

When describing Mylo, Bolt Threads frequently use the word ‘unleather’. Rather than striving for a biobased equivalent, they seek to create a superior and ethical version of the product. On their Mylo website and Instagram page (@mylo_unleather), they state Mylo is, ‘the complex latticework of underground fibres so strong they hold the planet together’ (‘Meet Mylo’ 2020). It is through this notion of ‘unleather’ that a twin narrative forms, marrying the avoidance of unethical treatment of animals with improved environmental outcomes.

Alongside established fashion brands, new ones have emerged that fuse the principles of cleaner production with biotechnology as a partnership with nature. Pangeia founder, Miroslava Duma, exemplifies this in describing the brand’s philosophy as ‘high-tech naturalism’. Describing the ten-year development of their Flower Down technology, Chief Innovation Officer Parkes said:

> We use waste wildflowers, augmented with high-tech cellulosic aerogel which allows us to preserve and create the thermal capabilities of the flowers. The high-tech material science of biotech, combined with advanced digital processes, help us utilise waste in more effective ways (Quoted in Conlon, 2020).

Although established corporations are deploying biotechnology innovations in fibre production (e.g., the chemical company Dupont with their product Sorona), many of the new material companies are start-ups seeking to disrupt the establishment. For example, Suzanne Lee has been a trailblazer in this regard, bringing bacterial cellulose to international attention as a ‘grow your own fabric’, and more recently, as Chief Creative Officer for the biotechnology start-up Modern Meadow. Lee identified (2019), ‘It used to be that the tools of biotechnology were the preserve of powerful, multinational chemical and biotech companies... But this 21st-century material revolution is being led by start-ups with small teams and limited capital.' Lee's Biofabricate is a platform and consulting agency assisting biomaterial innovators and brands in incorporating sustainability and biology into their designs with the tagline, 'built with biology, not oil'. These new materials and processes offer urgently-needed solutions and are a means to tame and rein in the excesses of a destructive system. These start-ups are agile and promise to disrupt the industry.

The future described in these narratives, from both start-ups and big companies is one in which biotechnology can provide cleaner and more ethical production processes and offer a transition away from fossil fuels. Yet this position is open to critique. Despite these examples and the growing investment in biotechnology, virgin fossil oil-derived feedstocks remain cheaper. The recent Textiles Exchange Preferred Fibre and Materials Market Report (2020) notes the limited uptake these technologies currently have. Regulatory action may be required, and signs of this are suggested by action in the European Union (2020) which seeks to scale up clean technologies for a circular economy. Indeed, of all the biotechnology examples described earlier, it is the use of enzymes to finish textiles that is the most established in the industry (Shen and Smith, 2015; for specific examples, see Eid and Ibrahim, 2021).

Rewilding: open-access biotechnology for home grown production

Rewilding examines how biotechnology is positioned in the space of artisanal, home grown production practices, in which users and tinkerers experiment on the margins of industry. The concept of rewilding means to restore and regenerate wild places (e.g. Monbiot 2014). In this context, we co-opt the term 'rewilding' to express the desire to return to slower, more traditional, ecocentric forms of fashion making and wearing. The premise, first explored in Payne (2019), looks for forms of fashion practice occurring outside the mainstream industry. Relatedly, Amy Twigger Holroyd (2016) proposes a 'fashion commons' way of making and wearing clothing outside of the dominant model, fostering making and repair practices. Rewilding fashion aligns with notions of post-growth fashion proposed by Fletcher (2016), which includes an individual's resourceful skills and practices. Within materials production, rewilding examples can be seen in the agro-forestry approach of Far Farm, as well as in the Fibershed movement which proposes re-localised networks of organic fibre, textile and clothing production.

Inherent to the rewilding ideas may be a caution around the 'synthetic' and the 'artificial' leading, for example, to a perception of organic cotton as preferable to genetically modified cotton. In part, this caution may be due to socially-constructed categories of what is natural and what is unnatural (e.g. see the media analysis of references to genetics and biotech by Hansen 2006). However, the caution may also be political and based on concerns regarding the corporate ownership of biotechnology. The activist and eco-feminist Vandana Shiva has been a vocal opponent of GMO cotton in part for the power the agricultural biotechnology companies exert over Indian farmers (Thomas & Tavernier, 2017). A recent critique of biotechnology's application in fashion from the Fibershed movement captures both these arguments in urging caution, arguing 'there is nothing natural or sustainable about synthetic biology's high-tech (and potentially high-risk) approach to novel fibre production' and questioning its sustainability due to the impact on the livelihoods of traditional fibre growers (ETC & Fibershed 2020, 2).

While fashion biotechnology is commonly viewed as involving high-tech laboratory-derived textiles, alternative views on kinship with nature and 'wildness' also offer a pathway for designers and entrepreneurs to apply biotechnology in small-scale decentralised models of textile production. The notion of 'fringe biotechnology' refers to alternative biotechnology practices on the margins of corporate and institutional biotechnology (Vaage 2017) with bacterial cellulose an example of a biotextile that lends itself well to the home-made and home-grown. Bacterial cellulose is a leather-like alternative that is traditionally made with water, sugar, and tea in the kombucha process. Industrially speaking, bacterial cellulose has potential in a variety of industries including food, biomedical, pharmaceutical, paper, and electronics. Yet, bacterial cellulose has been taken up in the realm of makers and tinkerers; community groups have emerged for the development of this material. In the span of a few years, community groups have evolved online with the Facebook public group Fungal Materials & Biofabrication and its 15,900 members 'openly sharing how-to and DIY information about using fungi for clothing, construction, and other material uses' (Fungal Materials & Biofabrication, 2020). Regarding the kombucha tea and SCOBY (symbiotic culture of bacteria and yeast) that are utilized in bacterial cellulose, groups exist for kombucha brewers to ask questions and share results: Kombucha Nation: Cultures, Health, and Healing! (private group - 80,200 members), Kombucha Home Brewing (private group - 20,100 members), Kombucha Brewers (private group - 34,000 members).

These communities extend the notion that bacterial cellulose can become a homegrown, DIY production for people rather than the 'taming' approach of biotechnological industrial production seen with a variety of bio-based equivalents and textiles. During the COVID-19 pandemic, two designers created a DIY bacterial cellulose face mask that captured international attention due to its biodegradability and the necessity of protective equipment ('Face Mask …' 2020), highlighting further the opportunities for grow-it-yourself textiles. Further examples supporting bacterial cellulose in a home-grown environment with open-source material include the open-access BioFab Forum which contains free resources such as starter guides and manuals that are 'tried and tested' and a good starting point for interested beginners. These suggest opportunities for online communities to take up and democratise synbio.

In addition to online groups permeating the rewilding stage from a digital media perspective, makerspaces and Fablabs around the world are sharing resources for the development of biomaterials, biotextiles, and sustainability in physical spaces. In Australia, the State Library of Queensland ran bacterial cellulose workshops from 2014-18 and produced starter kits and online instructions for the public. An approach for students to experiment with bacterial cellulose as a means to grow-your-own material can be seen in a number of design schools including the authors' own university[5] and UC Davis California (Cogdell 2019). In the US, the artisanal cheesemaker Sacha Laurin also runs 'kombucha couture' workshops to teach people to grow their own textiles (Chung 2019).

Bridging the gap between the DIY and the lab, Fablabs serve to foster communities for biotechnology and biodesign practitioners, with notable example including BlueCity labs in the Netherlands which seeks to 'support the transition towards a biocircular economy by facilitating work & labspace for a growing community of bioneers. Bioneers establish examples for a regenerative economy within the planetary boundaries by doing and experimenting' (BlueCity Labs, n.d.). They use a new term, bioneers, to express those actively engaging a biocircular economy for the betterment of the earth. BlueCity Lab features wet and dry labs that are available as well as breakout spaces for a monthly membership fee.

Speculating: biotechnology as imagining alternative futures

Speculating examines biotechnology design propositions that hover on the boundaries of possibility, offering a method for open exploration of the 'entanglements' of human and more-than-human. Design fictions are a fruitful space for imagining new futures, termed as speculative or critical design (Dunne and Raby 2001). Within the realm of fashion and biotechnology, there have been many speculative design projects.

Stefa Schwabe created 'The Kernels of Chimaera', a prototype of what a biological, bacterial cellulose material factory may become, which automatically harvests new bacterial cellulose grown on the surface of the kombucha cultures (Schwabe 2012). Schwabe also designed 'Everyday Paper, Paper Everyday' which was an experiment that analysed how bacterial cellulose could be controlled and cultivated, rolled in an unlimited roll of biomaterial that consistently produces fresh bacterial cellulose similarly to how fabrics are bought and produced in rolls (Schwabe 2015). These speculations prompt a means to imagine an industrial production system for the bacterial cellulose pellicle. In a practical sense, the likely relative high cost of production of bacterial cellulose compared with other leather-like textiles lends itself well to artisanal pursuits (Dourado et al., 2016).

Additional examples include artist Diana Scherer (2019), who develops 'exercises in rootsystem domestication' in which new textiles are formed through root systems trained into latticework (examined in Zhou et al 2020). Designer Carole Collet (2016) presents an imaginary strawberry root lace, in which a lace grows from the plant roots. Suzanne Lee proposes that complete bacterial cellulose dresses or shoes may grow whole from engineered bacteria (Hemmings 2008; Biocouture 2014). Sacha Laurin, interviewed about her kombucha couture, flips the lack of durability of bacterial cellulose to become a positive way to imagine new modes of consumption: 'what if we buy a jacket and we know that it's going to break down and we've only got a season? It's like fashion with an expiration date and that's ok' (quoted in Chung 2019). Clothes would come with a bacterial cellulose repair patch, so if 'your outfit breaks, you just put this [bacterial cellulose patch] over and by tomorrow, it will have completely integrated'. From an advanced biotechnology standpoint, genetic toolkits for a particular bacterial cellulose-producing bacterial strain (*K. rhaeticus* iGEM) have been created that allow cell programming and tweaking of properties depending on its application (Florea *et al* 2016; Singh *et al* 2020).

Speculating in the scientific context sees experimental work in the lab yield propositions for new materials and processes using biotechnology. Already, as Bensuade Vincent (2013) has observed, the synbio community is enraptured with 'the promises and imagined futures of plenty' and imagination is core to this. Similar to the concepts of 'self-repair' and engineered living material proposed by the designers above, researchers have developed bacterial cellulose with advanced properties using engineered microorganisms (Florea *et al* 2016; Walker *et al* 2019; Gilbert *et al* 2019). Termed a 'synthetic "symbiotic culture of bacteria and yeast"' or Syn-SCOBY, the living materials are engineered with the ability to sense environmental pollutants, or to allow patterning on the surface (Gilbert *et al* 2019). Research occurring in biotechnology labs can represent a fusion of scientific enquiry, speculation and entrepreneurship in pushing the boundaries of knowledge and seeking new applications for this knowledge. As an example, synbio student teams compete in the International Genetically Engineered Machine (iGEM) competition, which is predicated on the inventive use of synbio to solve real world problems with several projects investigating new textile dyeing technologies.

As neither the 'taming' or the 'rewilding' approaches to biotechnology in fashion have gained wide uptake, many of their proponents use the power of speculation and imagination in sharing their prototyped materials. Speculation can also provoke further ethical questions to explore: Do microbes have rights? Can a leather produced by living bacteria be called 'vegan'? Are cell factories preferable to human factories? Speculation also offers the potential to interrogate taming and rewilding approaches together. For example, in the case of bacterial cellulose, could wafers of the SCOBY be lab-grown and optimised with the capacity of industrial biotechnology, and be provided in a DIY kit to users to ensure grassroots community access to the material? How could engineered microbial systems be made available, released and regulated for the use of the engineered organisms by the public?

Concluding remarks

The status quo in fashion and textile production and usage is unsustainable, and symptomatic of the wider unsustainability of industrial societies in their present form. Fashion needs to transform in response to environmental degradation and in calls from researchers and industry, biotechnology is proposed as a path to do so (Collet 2016; 2018; Lee 2019). It is through biotechnology that novel fibres, materials and processes can be developed to provide solutions to the ills of the fashion and textile industry. Yet there are many ways to view these technologies and their role in fashion's future. Beyond the technocratic approach, biotechnology may be framed as a fusion with the more-than-human, recalling Bolt Thread's (n.d.) Mylo leather formed from the mycelium that 'hold[s] the world together.' Our aim in this article was to examine the present applications of biotechnology in fashion and offer a way for researchers and designers to consider the philosophical and practical implications. If one takes a 'flat ontology' as we have argued in which the human and the non-human are inevitably entwined, the questions posed are less about the degree to which biotechnology is natural or artificial and instead become more about *how* is biotechnology deployed, for whom, and to what end?

The recent narratives of fashion biotechnology we identify here as taming, rewilding, and speculating, suggest an agenda for future research in fashion biotechnology. Taming examines ways in which biotechnology can offer alternatives that control and reduce environmental impacts of textile production at scale, particularly in the replacement of existing fossil-fuel based fibres with bio-based equivalents. High-tech approaches include synthetic biology to develop artificial spider silk and synthetic fibre precursors. These technologies and processes require large investments to bring them to commercial scale and buy-in from existing supply chain actors. Although there is growing interest, the market for these new materials remains mostly niche for now, although some technologies such as Dupont's Sorona fibre are made at large scale using a proportion of bio-derived materials. Research required includes rigorous demonstration that the new processes and materials have less environmental impact than their alternatives, as well as research questions around pathways to scale and impact (including impact on livelihoods in traditional fibre industries). Politically-speaking, an open question remains as to whether these technologies may ultimately serve to perpetuate an unsustainable system.

In contrast, the 'rewilding' practices can be positioned as operating on the margins of the larger fashion system. Although many proponents of what may be termed an 'ecocentric' approach to fashion's future may be cautious of the seemingly 'unnatural' and 'synthetic' propositions of biotechnology, practices in home-grown bacterial cellulose, whether using native or engineered microorganisms, point to a slower, gentler, low-fi pathway to using biotechnology in the home and community. Research and investment here are also required: how may growers and makers be empowered to engage with these materials (in keeping with the aim of the citizen science movement, for example), and what are the benefits for individuals and communities? What kinds of resources and learning materials will the safe and democratic use of biotechnology require, and how does one provide open-source access to the tools needed to engineer biology and optimise processes?

Speculative practice points to the rich opportunity biotechnology offers artists, designers and scientists to enact imaginative propositions for making and using textiles. Speculative practice can become the breeding ground for start-ups offering new materials – whether with the idea of scaling up (to commercialise) or scaling out (to the community). Yet speculation also offers a means to reflect upon the relationships between human and more-than-human, working in partnership. Together, the combinations of taming, rewilding and speculating can offer many possibilities for the future of fashion: biotechnology working *with* and *for* the more-than-human, biotechnology democratised and accessible, and last, biotechnology as a means for imagination and invention.

Notes

1. Websites and databases searched including WGSN, Business of Fashion, Dezeen, just-style, Fashion Network, Women's Wear Daily, Vogue, and Technical Textile, initially using the keywords 'fashion' and 'biotechnology' and compiled into a database of articles
2. For a detailed analysis applying ANT to fashion, see Entwistle (2016)
3. This table is adapted from Collet (2016). It contains two meanings for the word synthetic. When used in the phrase petroleum-derived synthetic fibres, synthetic is defined as being man-made and not natural fibres. However, when discussing bio-derived fibres, synthetic is used to describe synthetically engineered fibres or organisms. Synthetically engineered means organisms or materials that have been genetically enhanced for specific purposes.
4. The reported dyeing process utilizes an engineered bacterial strain to produce indican, a stabilised derivative of indoxyl that resists auto-oxidation to indigo dye due to the

attachment of a glucose protecting group. The glucose protecting group was attached using a newly discovered and characterised glycosyltransferase enzyme from the indigo plant Polygonum tinctorium (Hsu et al. 2018). Applying a β-glucosidase enzyme removes the glucose protecting group from indican to re-form indoxyl that subsequently oxidises and forms indigo crystals on cotton fibres.

5. In partnership with Dr Peter Musk at State Library of Queensland (SLQ), article co-author Alice Payne with colleague Dean Brough ran classes for first year fashion design students on growing BC from 2014-18, with outcomes presented for public exhibition. Article co-author Luis Quijano also collaborated with SLQ in 2017.

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References

Abdulla, H. 2018a. Nanollose makes first garment from tree-free rayon. *just-style*, November 1. https://www-just-style-com.ezp01.library.qut.edu.au/news /nanollose -makes-first-garment-from-tree-free-rayon_id134889.aspx

Abdulla, H. 2018b. Colorifix raises $3m funding to scale up biological dyeing. just-style, December 19. https://www-just-style-com.ezp01.library.qut.edu.au/news/ colorifix-raises-3m-funding-to-scale-up-biological-dyeing_id135271.aspx.

Bensaude Vincent, B. (2013). Between the possible and the actual: Philosophical perspectives on the design of synthetic organisms. Futures, 48, 23–31. https://doi.org/10.1016/j.futures.2013.02.006

BlueCity Labs. 2020. *BlueCity Lab*. Accessed 23 October 2020. https://www.bluecitylab.nl/

Chung, N. 2019. "Sacha Laurin: A Creative Cheese Maker and Kombucha Fashion Designer with an Alchemist's Touch for Wielding the Power of Bacteria". *Land and Ladle*, December 19. https://www.landandladle.com/sacha-laurin-a-creative-cheese-maker-and-kombucha-fashion-designer-with-an-alchemists-touch-for-wielding-the-power-of-bacterias/

Cogdell, C. 2019. "Sustainable Biodesign Innovation: Integrating Designers, Engineers." In *Sustainable Design and Manufacturing 2019: Proceedings of the*

6th International Conference on Sustainable Design and Manufacturing (KES-SDM 19), 155: 23-33. doi: https://doi.org/10.1007/978-981-13-9271-9_3

Collet, Carole. 2016. "Could Synthetic Biology Lead to Sustainable Textile Manufacturing?". In *Routledge Handbook of Sustainability and Fashion*, edited by Fletcher, Kate and Mathilda Tham, 191-200.

Conty, A. F.. 2018. “The Politics of Nature: New Materialist Responses to the Anthropocene.” *Theory, Culture & Society*, 35(7-8): 73–96. doi: https://doi.org/10.1177/0263276418802891

Dhivya, K., Sathish, S., Balakrishnan, N., Udayasuriyan, V., & D. Sudhakar. 2016. “Genetic engineering of cotton with a novel cry2AX1 gene to impart insect resistance against Helicoverpa armigera.” *Crop Breeding and Applied Biotechnology*, 16(3): 205-212. doi: https://doi.org/10.1590/1984-70332016v16n3a31

Dourado, F., Fontão, A., Leal, M., Rodrigues, A. C., and M. Gama. 2016. "Process modeling and techno-economic evaluation of an industrial bacterial nanocellulose fermentation process" Chap. 12 in *Bacterial Nanocellulose From Biotechnology to Bio-Economy*, edited by Miguel Gama, Fernando Dourado and Stanislaw Bielecki. Amsterdam: Elsevier

Dunne, A., and F. Raby. 2001. *Design Noir: The Secret Life of Electronic Objects*. London, Basel: Birkhauser,

Eid, B. M., and N. A. Ibrahim. 2021. Recent developments in sustainable finishing of cellulosic textiles employing biotechnology. *Journal of Cleaner Production*, 284, 124701. DOI: https://doi.org/10.1016/j.jclepro.2020.124701

Enjoli, A. 2018. These biodegradable vegan leather alternatives are fashion's future (so long, PVC). *Peaceful Dumpling*, May 30. https://www.peacefuldumpling.com/leather-alternatives

Entwistle, J. 2016. "Bruno Latour: Actor-Network-Theory and Fashion." In *Thinking through Fashion: A Guide to Key Theorists*, edited by Rocamora, Agnès and Anneke Smelik, 269-284. London and New York: I.B. Taurus.

ETC & Fibershed. 2020. *Genetically Engineered Clothes: Synthetic Biology's New Spin on Fast Fashion*. http://fibershed.org/wp-content/uploads/2018/09/ETC_SynbioFabricsReport_8Fsm.pdf

European Commission. 2020. *Circular Economy Action Plan: For a cleaner and more competitive Europe*. European Commission. https://ec.europa.eu/environment/circular-economy/pdf/new_circular_economy_action_plan.pdf

"Face mask made out of bacterial cellulose". 2020. *Biooekonomie.de*, June 16. https://biooekonomie.de/en/nachrichten/face-mask-made-bacterial-cellulose

Fletcher, K. 2014. "Design for Sustainability in Fashion and Textiles." In *Handbook* *of Fashion Studies*, edited by Black, Sandy, de la Haye, Amy, Root, Regina, Rocamora, Agnès and Helen Thomas, 562-579. London and New York: Bloomsbury Academic.

Fletcher, K. 2016. *Craft of use post-growth fashion*. Abingdon, Oxon.: Routledge.

Florea, Michael, Henrik Hagemann, Gabriella Santosa, James Abbott, Chris N. Micklem, Xenia Spencer-Milnes, Laura de Arroyo Garcia, et al. "Engineering Control of Bacterial Cellulose Production Using a Genetic Toolkit and a New Cellulose-Producing Strain." Proceedings of the National Academy of Sciences 113, no. 24 (2016): E3431-E40. https://doi.org/10.1073/pnas.1522985113. https://www.pnas.org/content/pnas/113/24/E3431.full.pdf.

Fungal Materials & Biofabrication. (2020). *Fungal Materials & Biofabrication*. https://www.facebook.com/groups/fungalmaterials

Gabrys, J. 2013, 'Plastic and the work of the biodegradable' in *Accumulation: The material politics of plastic* edited by Gabrys, Jennifer, Hawkins, Gay and Mike Michael. London: Routledge, 208-217.

Genomatica. 2020. "Genomatica Hits Industry-First Milestone in Nylon Sustainability" January 2020. https://www.genomatica.com/worlds-first-ton-of-renewable-nylon-intermediate/

Gilbert, Charlie, Tzu-Chieh Tang, Wolfgang Ott, Brandon A. Dorr, William M. Shaw, George L. Sun, Timothy K. Lu, and Tom Ellis. "Living Materials with Programmable Functionalities Grown from Engineered Microbial Co-Cultures." bioRxiv (2019): 2019.12.20.882472. https://doi.org/10.1101/2019.12.20.882472. https://www.biorxiv.org/content/biorxiv/early/2019/12/20/2019.12.20.882472.full.pdf.

Hansen, A. 2006. "Tampering with Nature: 'nature' and the 'natural' in Media Coverage of Genetics and Biotechnology." *Media, Culture & Society* 28(6): 811–834. doi: https://doi.org/10.1177/0163443706067026

Haraway, D. J. 2012. *Staying with the Trouble: Making Kin in the Chthulucene*. Durham and London: Duke University Press

Hirsh, S. 2020. These companies are making vegan leather out of plants instead of plastic. *GreenMatters*, March 5. https://www.greenmatters.com/p/vegan-leather-made-from-plants

Hsu, T. M., Welner, D. H., Russ, Z. N., Cervantes, B., Prathuri, R. L., Adams, P. D., and J. E. Duebeter. 2018. "Employing a biochemical protecting group for a sustainable indigo dyeing strategy." *Nature Chemical Biology* 14: 256-261. doi: https://doi.org/10.1038/NCHEMBIO.2552

Latour, B. 1993. *We Have Never Been Modern*. Cambridge, MA: Harvard University Press.

Lee, S. Y., Kim, H. U., Chae, T. U., Cho, J.S., Kim, J. W., Shin, J. H., & J. H. Shin et al. 2019. A comprehensive metabolic map for production of bio-based chemicals. *Nature Catalysis*, 2: 18-33. doi: https://doi.org/10.1038/s41929-018-0212-4

Lee, S. 2019. "Why "biofabrication" is the next industrial revolution". TEDSummit. https://www.ted.com/talks/suzanne_lee_why_biofabrication_is_the_next_industrial_revolution

Lie, S. A. N. 2016. *Philosophy of Nature: Rethinking Naturalness*. London, [England]: Earthscan.

Miceli, C. 2018. "Spider silk is five times stronger than steel - now, scientists know why." *Science Mag*, November 20. https://www.sciencemag.org/news/2018/11/spider-silk-five-times-stronger-steel-now-scientists-know-why

"Meet Mylo." 2020. *Mylo-Unleather*. Accessed 12 October 2020. https://www.mylo-unleather.com/

Monbiot, G. *Feral: Rewilding the Land, the Sea, and Human Life*. Chicago and London: University of Chicago Press, 2014.

Molloy, J. 2017. “Cambridge SynBio Startup Colorifix Wins Rainbow Seed Fund “Breaking New Ground” Award at Bio-start Competition” https://www.synbio.cam.ac.uk/news/cambridge-synbio-startup-colorifix-wins-rainbow-seed-fund-201cbreaking-new-ground201d-award-at-bio-start-competition

Niinimäki, K., Peters, G., Dahlbo, H., Perry, P., Rissanen, T., and A. Gwilt. 2020. "The environmental price of fast fashion." *Nature Reviews Earth & Environment* 1: 189-200. doi: https://doi.org/10.1038/s43017-020-0039-9

Payne, A. 2019. Fashion Futuring in the Anthropocene: Sustainable Fashion as “Taming” and “Rewilding.” *Fashion Theory - Journal of Dress Body and Culture*, 23(1). https://doi.org/10.1080/1362704X.2017.1374097

Pickar-Oliver, A., Gersbach, C.A. 2019. The next generation of CRISPR–Cas technologies and applications. *Nature Reviews Molecular Cell Biology* **20:** 490–507. https://doi.org/10.1038/s41580-019-0131-5

Ringstrom, A., and S., McDill, 2019. The H&M-Backed Start-Up Using Microbes to Dye Fabric. *Business of Fashion*, November 27. https://www.businessoffashion .com/articles/news-analysis/hm-backed-startup-puts-bacteria-to-work-in-green-dyeing-process

Russel, M. 2019. Tinctorium uses bacteria to produce sustainable indigo. *just-style*, December 3. https://www-just-style-com.ezp01.library.qut.edu.au/news/

tinctorium-uses-bacteria-to-produce-sustainable-indigo_id137642.aspx

Scherer, D. 2019. "Interview with Diana Scherer: Weaving roots at the interface between art, fashion and science. *Plants People Planet* 1: 142-145. doi:10.1002/ppp3.48

Schewabe, S. 2012. “Living Artifacts.” *Design Interaction*, September 9. http://www.di12.rca.ac.uk/?projects=living-artefacts

Schewabe, S. 2015. “The Kernels of Chimaera.” *Studio Stefan Schwabe*, June 28. http://www.stschwabe.com/work/KoC

Sewell, C. 2015. From apples to kombucha tea: See the ingenious way designers are making vegan leather. *PETA*, July 10. https://www.peta.org/living/personal-care-fashion/vegan-leather-chic-sustainable-and-fruity/

Singh, A., Walker, K. T., Ledesma-Amaro, R., & Ellis, T. (2020). Engineering Bacterial Cellulose by Synthetic Biology. International Journal of Molecular Sciences, 21(23), 9185. https://doi.org/10.3390/ijms21239185

“Stella McCartney and Bolt Threads Announce a New Partnership Focused on Sustainable Fashion and Luxury Materials Development.” 2017. *Bolt Threads*, July 20. https://boltthreads.com/2017/07/20/stella-mccartney-and-bolt-threads-announce-a-new-partnership-focused-on-sustainable-fashion-and-luxury-materials-development/

Textile Exchange. 2020. *Preferred Fiber & Materials Market Report 2020*. Textile Exchange. https://textileexchange.org/wp-content/uploads/2020/06/Textile-Exchange_Preferred-Fiber-Material-Market-Report_2020.pdf

Thomas, G., and J. D. Tavernier. 2017. Farmer-suicide in India: Debating the role of biotechnology. *Life Sciences, Society and Policy* 13(8): 1-21. doi: 10.1186/s40504-017-0052-z

Holroyd, A. T. 2016. "Openness." In *The Handbook of Sustainability and Fashion*, edited by Fletcher, Kate and Mathilda Tham, 253-261. Abingdon, Oxon. and New York: Routledge.

Twilley, N. 2017. In the future we'll all wear spider silk. *The New Yorker*, March 12. https://www.newyorker.com/tech/annals-of-technology/in-the-future-well-all-wear-spider-silk

UK House of Commons Environmental Audit Committee. 2019. *Fixing Fashion: Clothing Consumption and Sustainability: Sixteenth Report of Session 2017–19*. House of Commons Environmental Audit Committee. https://publications.parliament.uk/pa/cm201719/cmselect/cmenvaud/1952/report-files/195204.htm.

Walker, Kenneth T., Vivianne J. Goosens, Akashaditya Das, Alicia E. Graham, and Tom Ellis. "Engineered Cell-to-Cell Signalling within Growing Bacterial

Cellulose Pellicles." Microbial Biotechnology 12, no. 4 (2019): 611-19. https://doi.org/https://doi.org/10.1111/1751-7915.13340. https://sfamjournals.onlinelibrary.wiley.com/doi/abs/10.1111/1751-7915.13340.

Wodak, J. (2020). (Human-Inflected) Evolution in an Age of (Human-Induced) Extinction: Synthetic Biology Meets the Anthropocene. Humanities, 9(4), 126. https://doi.org/10.3390/h9040126

Wood-Black, F. 2018. "The Steel Strength of Featherweight Spider Silk." *inChemistry*, July 30. https://inchemistry.acs.org/content/inchemistry/en/atomic-news/spider-webs.html

Williams, R. 1986. *Keywords: A Vocabulary of Culture and Society*. Rev. ed. New York: Oxford University Press.

Zhou, J., Barati, B., Wu, J., Scherer, D., and E. Karana. 2020. "Digital Biofabrication to Realize the Potentials of Plant Roots for Product Design." *Bio-Design and Manufacturing*, 1-12. doi: https://doi.org/10.1007/s42242-020-00088-2.