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Perspective

Bioengineering textiles across scales for a sustainable circular economy

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SUMMARY

Current textile production and processing practices provide materials with desirable performance properties, such as stretch and moisture management, but these processes are leading contributors to global greenhouse gas emissions, microplastic pollution, and toxic wastewater. Fortunately, green alternatives to current textile fibers that support a transition to a sustainable, circular materials economy are within reach. Bioengineering of fibers at the nano-, micro-, and macroscale provides several avenues to improve both the environmental impacts and technical performance of textile materials. Herein, we provide an overview of recent efforts to bioengineer fibers and textiles from the biopolymer components to biofabrication schemes. These include the genetic engineering of microorganisms for biofabrication, green chemistry processing of raw materials, and green manufacturing techniques. This overview informs a discussion on the future outlook of sustainable biotextile production, with a focus on utilization of waste streams to both improve the circularity and commercial viability of the processes.

The bigger picture

Challenges and opportunities

- The development of bio-based, recyclable fibers that replicate the materials properties of commercial textile fibers.
- The timely degradation of bioengineered fibers with advanced properties (e.g., elasticity, wicking) within natural soil and marine environments.
- A circular economy that transforms waste streams into engineered, biodegradable fibers for sustainable textiles.

INTRODUCTION

Biofabrication of materials will play a key role in facilitating the transition from an environmentally destructive linear economy to a cradle-to-cradle circular economy.[1,2] A circular economy seeks to emulate nature's cycling, using ecologically benign processes to close and minimize material and energy loops, with the central premise that infinitely reusing our materials can make industrialization compatible with sustainable development and climate stability. For example, the significant environmental impacts of plastic can be mitigated by adopting circular economy approaches, including closed-loop chemical recycling of synthetic polymers to monomers and programmed biodegradation.[3,4] New polymeric materials with appropriate mechanical properties that can be completely recycled back to monomer, repurposed for new uses, or readily degraded in the environment are currently being developed.[5–8] Bio-based strategies to design biodegradable materials with minimal carbon footprints are becoming an especially active area in the textile industry, as the production of both synthetic and natural textiles has significant environmental and climate impacts. To form synthetic textile fibers, such as nylon or elastane, a range of nonrenewable and non-recyclable resources and petrochemicals are used. Concurrently, the production of natural fibers, such as cotton, and degradable polymer fibers, such as polylactic acid, produced from corn-derived ethanol, rely on non-sustainable industrial agricultural practices.[9] In addition to the raw fiber production, the tanning, dyeing, and finishing agents used to produce the aesthetic and performance properties of textiles create an overall linear process that is chemical, water, and energy intensive.[10] For example, the current textile industry contributes to 10% of global carbon emissions[11] and 20% of global waste water.[12] Critically, the production of some synthetic fibers results in the formation of microplastics and it is estimated that 35% of marine microplastic pollution is derived from the textile industry.[13] This microplastic pollution is particularly harmful, as microplastics have been shown to disrupt endocrine signaling and accumulate throughout the food web and have been found in intestinal tracts of marine mammals and humans, and recently, in human placentas.[14–19] Moreover, climate impacts of the linear economy, including dramatic disturbances or reductions in fresh water access and biodiversity, disproportionately affect indigenous communities, people of color, the elderly, women, and children.[20] These impacts profoundly affect human rights and social justice, and limit access to education critical to global sustainable development. Addressing the climate impacts of the textile industry would help achieve several of the United Nations Sustainable Development Goals (SDGs), including access to clean water and sanitation (SDG 6), responsible consumption and production (SDG 12), and climate action (SDG 13).

Despite the large manufacturing impacts of textiles, the dominant cradle-to-grave linear economy sends the equivalent of a truckload of clothing to a landfill every second,[15] leaching toxic dyes, plasticizers, and finishing agents into groundwater and releasing potent greenhouse gases into the atmosphere. In contrast, a circular economy is characterized by carbon efficiency, elimination of dependence on fossil feedstocks, and integration of industrial production with end-of-life reintegration of materials through complete recycling or natural biodegradation (Figure 1). As a part of this process, healthy soil is produced and acts as an important climate regulator,[21] with the potential to mitigate 23.8 Gt of CO_2-equivalent per year globally.[22]

Therefore, there is a pressing need to develop fabrication processes that create high-performance textiles with the requisite strength, ductility, and moisture management but that are biodegradable by and non-toxic to microorganisms in the environment. Synthetic biology and biofabrication have the potential to address this challenge through custom-designed organisms and bioinspired processes and can directly transform industrial side streams and byproducts into high-value materials with broad applications. For example, collagen fibers can be produced in genetically modified microbes to biofabricate leather and bio-utilization of rapidly renewable biopolymers, such as fungal mycelium, can create alternative leathers and fabrics.[23,24] Moreover, various biofabrication technologies, including 3D printing and green electrospinning,[25] coupled with microbial fermentation, provide significant opportunities for biotextiles with minimal waste in the production phase and a closed-loop life cycle. Importantly, the climate change mitigation potential of biofabrication processes and biomaterial products is estimated at 1–2.5 billion tons of CO_2-equivalent per year by 2030.[26] Greater climate change offsets may be achieved if bioengineering is used to disrupt conventional textile manufacturing, which is currently expected to constitute 25% of the global carbon budget by 2050.[15] The potential of biofabrication to engineer a range of materials, coupled with the enormous environmental impact of conventional textile manufacturing, has propelled research into more sustainable, bio-based textiles. Here, we present nano-, micro-, and macroscale bioengineering strategies for the sustainable production of textile fibers with broad application across sectors, including fashion, biomedical, and industrial applications, with potential to accelerate a paradigm shift to a circular materials economy.

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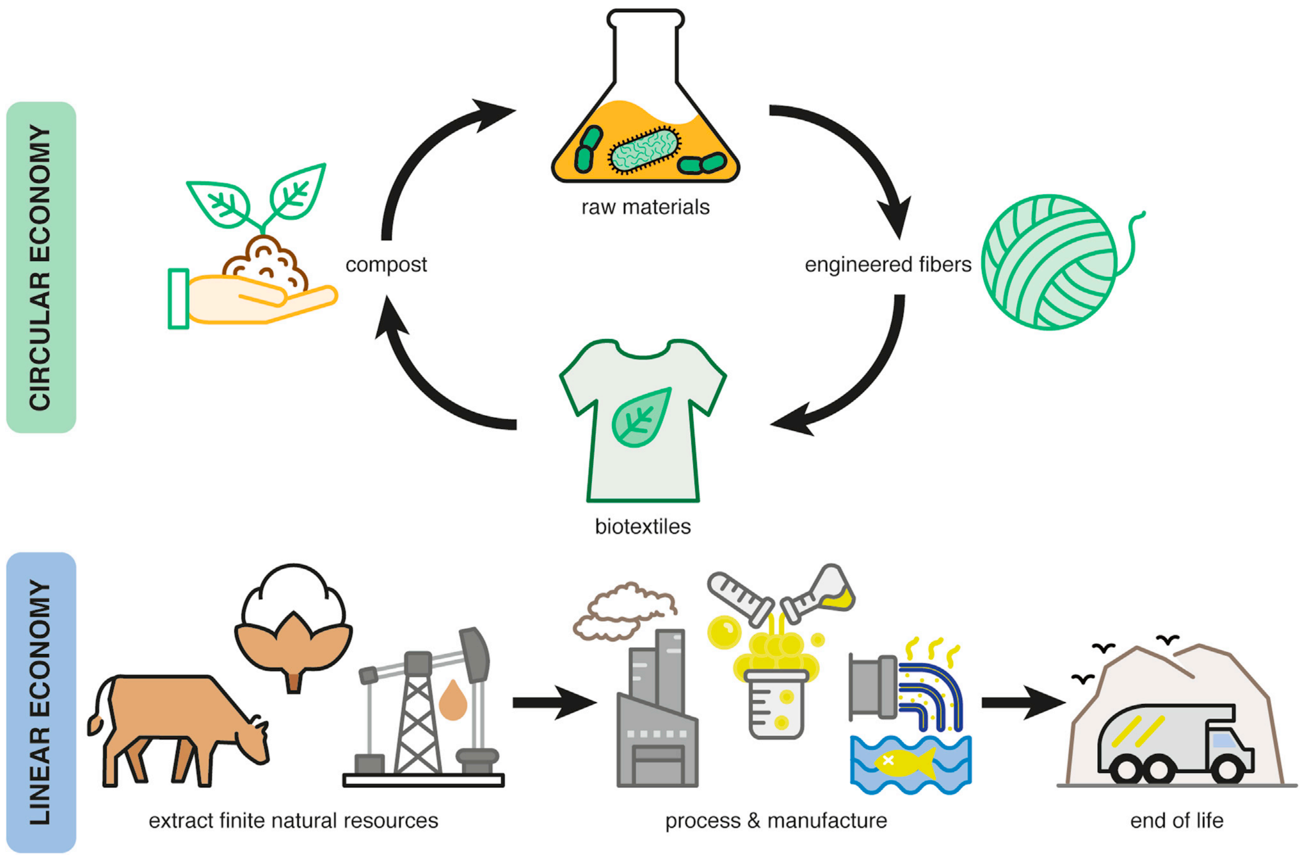

Figure 1. Comparison of circular and linear economies
Synthetic biology and biofabrication approaches offer a pathway to a circular textile economy. In this paradigm, biological building blocks are fermented or extracted from waste streams to create biopolymers, green chemistry processing links biopolymers into engineered fibers, and biomanufacturing produces degradable, performance biotextiles. Current textile production follows a linear cradle-to-grave economy with extraction of nonrenewable resources and chemical, water, and energy intensive manufacturing of non-recyclable products that end up in landfills or incinerators.

BIOENGINEERING AT THE NANOSCALE: PROTEIN ENGINEERING OF FIBER BIOPOLYMERS

Protein engineering offers the ability to produce materials with desired aesthetic and functional performance properties through molecular biomimicry. The range of colors, stretch, tensile strength, and moisture management properties society increasingly demands from textiles can all be found in biodiverse organisms in nature, without the environmental impact of toxic dyes, finishing agents, and petrochemical feedstocks. Engineering of protein building blocks allows for the strategic biomimicry of these desired aesthetic and performance properties in biotextiles. For example, introduction of binding domains on microbially expressed recombinant proteins facilitates their self-assembly into hybrid biomaterials, whereas inclusion of enzymatic cross-linking sites in such proteins offers a knob to tailor material properties at the molecular level with macroscale impact.

Advances in DNA synthesis and synthetic biology have enabled the bottom-up design of biomaterials via DNA-encoded functionality (Figure 2).[27,28] Although there is a direct connection from DNA sequence to protein sequence, the tools of synthetic biology enable broader metabolic engineering efforts to genetically encode polysaccharide and polyester materials as well.[29–31] These functional biopolymers have a host of outstanding properties, including color, elasticity, and biodegradability, that make

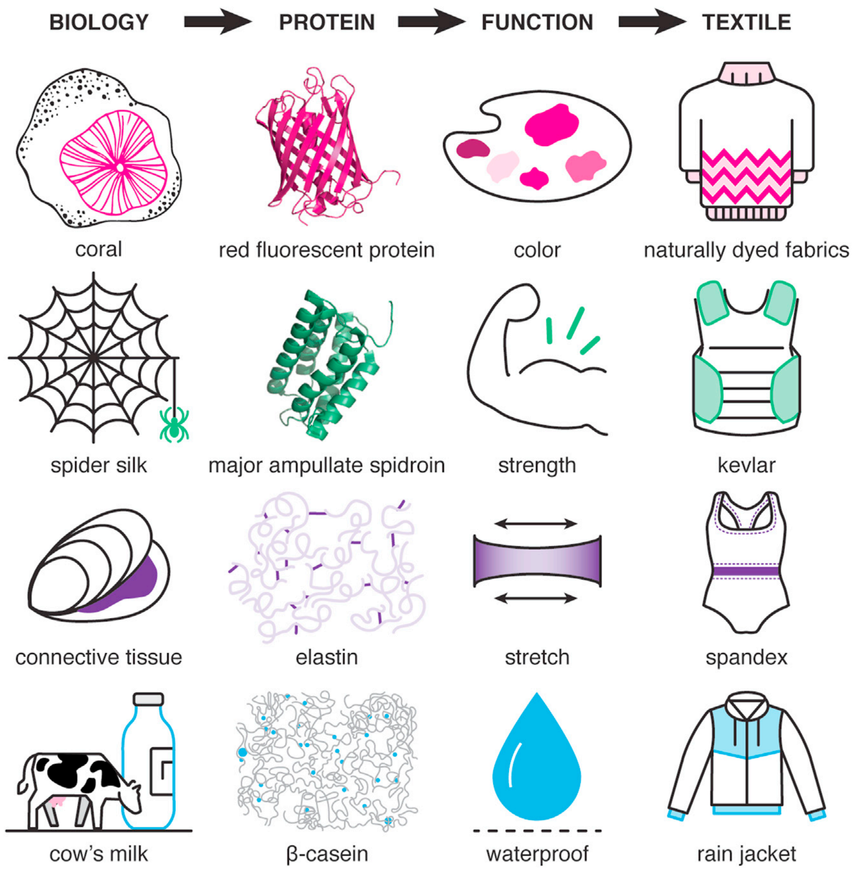

Figure 2. Protein engineering approaches for textiles

Protein engineering at the nanoscale can impart textiles with a range of performance properties. A biological feature is first selected, the protein that imparts this function is identified, and finally the protein is engineered and biosynthesized for incorporation into a textile. Several representative examples are shown schematically.

them well suited for use in circular economy biotextiles. However, the majority of engineered protein products have been designed for biomedical or pharmaceutical applications, largely due to the relatively high cost of production via fermentation. But, these desirable performance properties can be achieved in next-generation biomaterials using only a small percentage of protein biopolymer dopant.[32] For example, protein-based color can be imparted by minimal amounts of dye (<1%) due to the large extinction coefficients ($\sim 10^5$ M^{-1} cm^{-1}) of fluorescent proteins.[33] Similarly, stretch is currently provided to textile fibers with modest percentages (1%–10%) of synthetic elastane and it is envisioned that engineered proteins could be used in similar proportions to provide stretch while maintaining biodegradability. Substituting engineered protein biopolymers as low-percentage dopants in otherwise traditional carbon-intensive fibers can still significantly reduce the environmental impact. For example, substitution of elastane, which renders clothes unrecyclable when included at just 1%, with a biodegradable protein dopant can instantly improve the environmental impact and circularity of textile materials. Similarly, elimination of traditional dyes and mordants can significantly reduce the waste water generated from dyeing textiles. These positive impacts achieved with low-percentage incorporation of engineered biopolymers can be further compounded if combined with the sustainable production of bulk textile materials from waste streams or via fermentation. This provides an opportunity for research to identify and/or modify organisms for enhanced biopolymer yield when fed with inexpensive nutrients, particularly those obtained from waste streams. The ability to extract these nutrients from agro-industrial waste provides an additional opportunity to close energy and material loops across the most impactful industries in a circular economy.

Following the selection of a biomaterial property of interest, the protein biopolymer that confers this property must be identified (Figure 2). For example, the brilliant color of the *Discosoma* coral comes from a red fluorescent protein (RFP)[34] and the incredible strength of spider dragline fibers comes from the constituent proteins, major ampullate spidroins 1 and 2.[35] These protein components can then be designed at the DNA level, to directly reproduce the native protein recombinantly, to generate a fusion protein with the combined function of multiple proteins, or to engineer a synthetic, bioinspired protein. The DNA sequence can be assembled using the techniques of molecular biology, such as recursive directional ligation,[36] concatemerization,[37] or overlap extension rolling circle amplification,[38] depending on the desired size and repetitiveness of the target sequence.[28] These nanoscale engineering efforts have enabled the incorporation of red "dye" in bacterial nanocellulose fibers in the form of heterologously expressed RFP and the synthetic production of protein fibers with the tenacity and ductility of spider silk.[35,39] Although evolved and designed protein biopolymers have an outstanding array of functional properties that can be co-opted for textile fibers, they may not be able to readily reproduce all of the performance properties demanded by today's textile consumers. Fortunately, the microbial fermentation of polysaccharides or polyesters (e.g., polyhydroxyalkanoates) has the potential to provide sustainable, biodegradable fibers that replicate the durability and moisture management typically found in synthetic fibers.[40,41] In particular, the biosynthesis of natural and engineered microbial polyesters, such as poly-3-hydroxybutryate and polylactic acid, has the potential to directly displace synthetic polyester fibers derived from either petroleum or bio-based feedstocks.[42–44]

SYNTHETIC BIOLOGY AT THE MICROSCALE: FIBER ENGINEERING AND PROCESSING

In addition to engineering individual biopolymers at the DNA level, larger scale genetic changes can be made to the producing organisms in order to facilitate microscale fiber engineering. A host of organisms have been genetically engineered to produce biopolymer fibers for a range of textile applications. For example, plant cells have been engineered to produce cultured cotton, yeast strains have been developed to ferment collagen and spider silk, and *Gluconoacetobacter* has been engineered to improve the production of bacterial nanocellulose.[24,45–48] These materials have the potential to eliminate reliance on synthetic fertilizers, pesticides, and the large water and land demands of cellulosic and animal-based textiles, as well as the large carbon footprint, toxicity, and microplastic pollution of synthetic textiles.

Although efforts to engineer cotton plants to increase yield or produce colored cotton have demonstrated success,[49,50] we will focus here on the genetic engineering of microorganisms, as it harnesses green chemistry and mitigates the negative environmental impacts of industrial agriculture. Microbial fermentation is an ancient technique that can facilitate material innovation with agility and scalability. Critical to building the circular economy, microbes can utilize nutrients obtained from non-cellulosic agro-industrial waste for biosynthesis of high-value biopolymers for textiles. For example, bacterial nanocellulose is a naturally occurring, highly crystalline biopolymer produced extracellularly by bacteria, such as *Gluconacetobacter xylinus*.[51,52] This biopolymer has exceptional mechanical, thermochemical, and self-assembly properties that can be tailored with genetic editing of the producing organism, as well as with post-biosynthesis green chemistry processing. In addition, static cultivation enables biosynthesis of nanocellulose films to custom-tailored shapes to enable zero-waste patterning in the production phase.

Biofabrication opens opportunities for synthesizing as well as processing high-performance, bio-based textiles. Green chemistry processing using enzymes, such as amylase, cellulase, and pectinase, to name a few, have a long history and broad scope in various textile wet processing operations, such as debasting, desizing, scouring, and degumming cellulosic and protein fibers, as well as in dye decolorization in effluent.[53]

Enzyme-catalyzed reactions offer an inherently non-toxic and biocompatible approach to cross-linking biopolymer fibers, without the use of solvent-based chemistry, petrochemical plasticizers, or heavy metal reagents commonly used in textile manufacturing. In addition, the degree of selectivity, site specificity, and predictability of enzymatic cross-linking, enable high levels of control under mild processing conditions. For instance, microbial transglutaminase (TGase) has been used in biomedical applications, including tissue engineering scaffolds, pharmaceuticals, including PEGylation for protein therapeutics, food science, and edible packaging.[54,55] Microbial TGase has been used in wool and leather finishing processes to cross-link textile fibers with antimicrobial agents or biopolymer fillers.[56] These transglutaminases catalyze the transfer reaction between the primary amine of lysine and the γ-carboxyamide group of glutamine residues to form an isopeptide bond, creating cross-links in raw materials or fibers.[54,57–59] This family of enzymes has been shown to form these isopeptide bonds with limited dependence on the precise polypeptide sequence context, providing broad substrate specificity that has enabled industrial applications of TGases. The combination of the breadth and specificity of microbial TGase can also be exploited to efficiently cross-link a range of proteins, including recombinant proteins engineered with structure-based color and proteins obtained from agro-industrial side streams, to fabricate biodegradable textile fibers with both technical and environmental performance.[60] When coupled with the design of recombinant proteins tailored with specific binding domains to facilitate self-assembly, enzymatic cross-linking can also facilitate biofabrication of protein-polysaccharide biopolymer composites for textile applications (Figure 3A).

Likewise, microbial biosynthesis has been harnessed and coupled with green chemistry bioprocessing using lecithin phosphocholine to create a high-performance, bacterial nanocellulose bioleather. Prototype bioleather sneakers, made of bacterial nanocellulose biofabricated to the precise shape of the sneaker pattern, colored with plant and mineral dyes, and processed with the lecithin tanning method, are shown in Figure 3B.[41] This combined use of waste-to-resource strategies for microbial biofabrication and green processing for this biotextile yields up to an order-of-magnitude reduction in total environmental impact and a ~97% low carbon footprint relative to both synthetic (petrochemical-based) leather and canvas, as determined by life-cycle impact assessment (LCA), while also capable of natural biodegradation in soil.[41] Such green microscale bioengineering approaches can disrupt conventional manufacturing processes and mitigate the climate and environmental impacts of the global textile industry.

MOVING ACROSS SCALES: GREEN BIOMANUFACTURING OF BIOENGINEERED TEXTILES

The nano- and microscale bioengineering approaches described here have potential impact well beyond fashion and industrial textiles, with particular significance in biomedical applications in which biomimicry of native tissue and low toxicity are

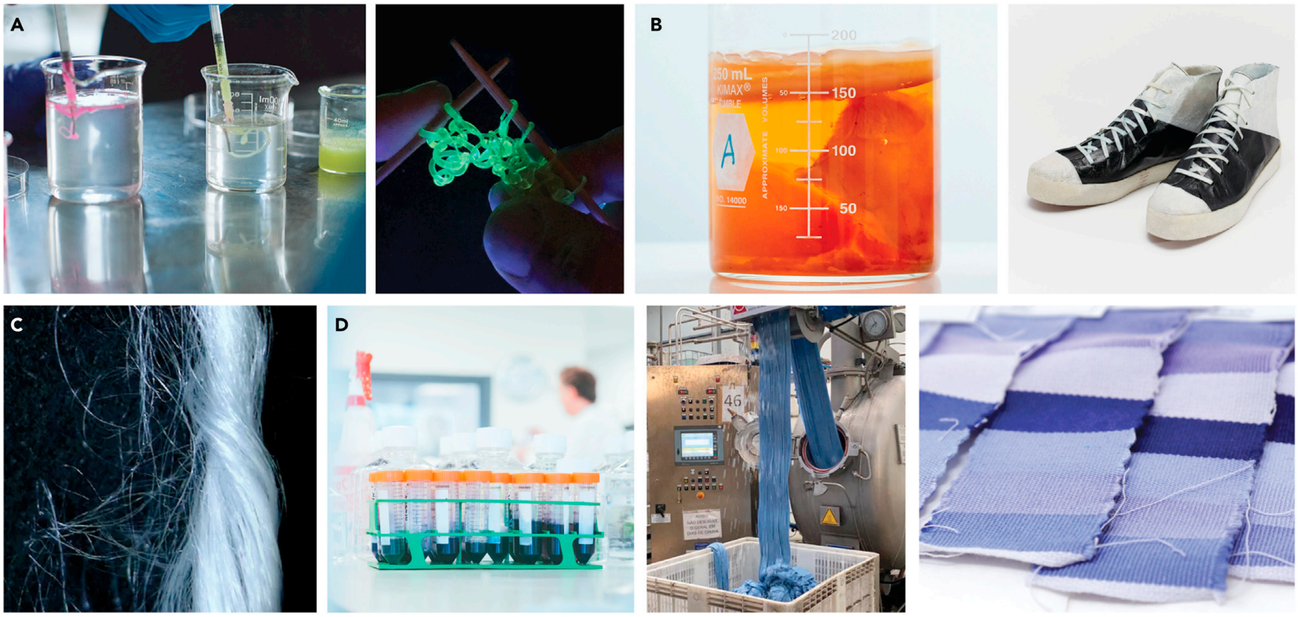

Figure 3. Examples of bioengineered textiles

(A) Werewool textile fibers—with color and fluorescence provided by proteins designed at the DNA level—being extruded (left) and knit (right).
(B) Biosynthesis of bacterial nanocellulose in a beaker (left) and bioleather sneakers made from bacterial nanocellulose (right) created in a collaboration between Schiros and Public School NY designers Dao-Yi Chow and Maxwell Osbourne using waste as a regenerative resource for the One x One Conscious Design Initiative, Slow Factory Foundation, Swarovski, and United Nations Office of Partnerships initiative.
(C) Spintex bioengineered silk fibers, created in a process that mimics how a spider spins silk at ambient conditions.
(D) Colorifix bacterial dyes produced by microorganisms (left), jet dyeing machine with bacterial dyes (middle), and dyed swatches (right). Credit for images: (A) Jon Brown for Werewool; (B) Sneakers: Jon Brown for One X One; (C) Spintex Engineering; and (D) Colorifix.

of paramount importance. In contrast to the relatively recent emphasis on environmental impact assessment in the apparel sector, life-cycle considerations of biomaterials used in tissue engineering and regenerative medicine have long focused on the biodegradability of the material in the physiological environment or its clearance from the body post-implantation and degradation. In particular, the alpha-hydroxy polyester family of polymers, specifically polylactic acid (PLA) and its co-polymer with polyglycolic acid (PGA), have dominated the field with their well-established record of biocompatibility. What makes these materials especially attractive is the fact that they are designed to stimulate regenerative cell responses and, moreover, as they degrade, *in vivo* space is made available for new tissue growth. Notably, these polymers break down via hydrolysis and the degradation products, lactic acid and/or glycolic acid, can be readily processed by the body through the Krebs cycle. The unique regenerative potential of these biomaterials also renders them ideal for biofabrication,[61,62] with tremendous translational potential across textile applications.

In the past decade and with the global push for sustainable manufacturing, industrial production of PLA has shifted significantly from chemical synthesis to fermentation with probiotics from the *Lactobacillus* genus, using simple sugars derived from corn or sugarcane as feeder stock.[63] Moreover, the ability to synthesize high molecular weight PLA has made it possible to manufacture PLA-based commodity products, replacing conventional fossil-plastics, such as polystyrene.[64] Note that the production of commodity thermoplastics via fossil fuel conversion is correlated to over 70 million tons of CO_2-equivalent per year in North America alone.[65] Thus, simply transitioning to such biomass-based biopolymers has the potential to cut greenhouse gas emissions by 16 M tons CO_2-equivalent per year (25% industry wide).[64]

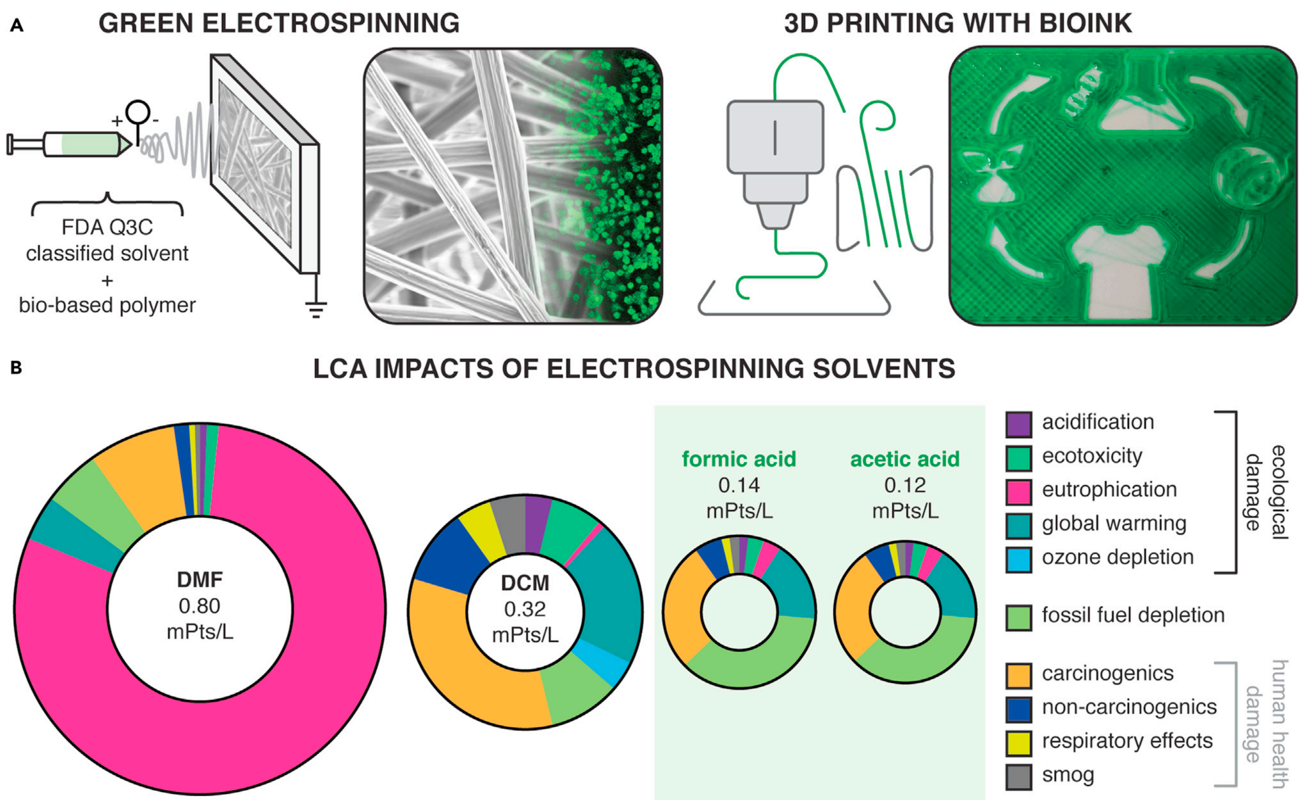

Figure 4. Green manufacturing of bioengineered materials

(A) (Left) Green electrospinning for low toxicity and eco-friendly nano- and microfibers and (right) 3D Printing with gelatin bioink for a circular economy.
(B) Crade-to-gate LCA for the manufacture of solvents commonly used for polymer electrospinning. All impacts, across the ten impacts shown, can be mitigated by using green solvents for electrospinning, such as formic or acetic acid, as these impart minimal ecological and human health damage, as well as resource depletion. Abbreviations: dimethylformamide (DMF), dichloromethane (DCM). Adapted with permission from Mosher et al.[25] Copyright 2021 IOP Publishing.

Indeed, it is exciting that for bio-based polymers, such as PLA or microbial cellulose, a cradle-to-cradle life cycle is now within reach, be it for biomedical or non-biomedical applications. As such, although the synthesis of bio-based polymers readily utilizes renewable feedstocks for biofabrication, the production of fibers and textiles based on these regenerative materials represents significant challenges for sustainable manufacturing. LCA, especially during the cradle-to-gate stage, revealed a tremendous environmental burden, from significant energy consumption for material processing (e.g. 51–59 MJ/kg for bio-based polyester)[65] to the widespread use of chemical solvents (e.g., methylene chloride, trifluoroethanol) that are harmful to both the environment and human health.

The growing awareness of and the pressing need for sustainable approaches to biomaterial production post-synthesis have propelled the development of "green" fabrication methods that seek to mitigate the negative impact of traditional manufacturing processes. As shown in Figure 4, two methods of particular relevance to fiber production and textile functionalization across length scales are "electrospinning" for producing nano- to microscale fibers and meshes, and "3D printing," a long-standing layer-by-layer deposition technique that is central to macroscale biofabrication and is fueling the recent renaissance in additive manufacturing across industries.

First reported in the 1990s for the production of nanoscale fibers,[66,67] electrospinning has been widely used to form nanofibers and microfibers, with high-fidelity control of fiber morphology, diameter, and architecture by fine tuning spinning parameters.[68–73] In addition to biofabrication for biomimetic tissue regeneration, electrospinning has been used to produce filtration meshes and smart textiles. For example, with the high surface area/volume ratio of electrospun meshes, the relative ease in forming composite fibers, plus the ability to tailor fiber architecture at the nano- and microscale, smart textiles imbued with a variety of functional characteristics (thermal regulation, waterproofing, and conductivity) have been explored.[74,75]

However, challenges in scaling up electrospinning for biomanufacturing, limited by both safety concerns and environmental risks associated with storage and disposal of volatile solvents used in traditional methods, have inspired a growing interest in green electrospinning.[25,76] Early approaches to green electrospinning focused on elimination of the solvent and using other means to liquify the polymer (e.g., heat), with more recent efforts on identifying green solvents with low ecological impact and minimal cytotoxicity to form polymer melts (e.g., acetic acid).[25,76] As shown in Figure 4B, LCA analysis (impact shown in relative mPts of impact/L of solvent used) revealed that environmental impacts of industrial solvents, such as dimethylformamide (DMF) or dichloromethane (DCM), are multifaceted, beyond just consideration of global warming and human health. For instance, the total impact score of 0.80 mPts/L for DMF stems from ecological damage attributed to solvent-induced eutrophication of water systems. In contrast, green solvents, such as formic acid or acetic acid, offer approximately 6–7-fold reduction in manufacturing impacts, with the added benefit of being non-volatile and thus much safer to store in large volumes for industrial use.

It is clear that by applying sustainability principles, electrospinning, one of the most popular methods for nano- to microscale fiber fabrication, can be converted from a process with detrimental environmental and health impacts to a green fiber production process. Most interestingly, green electrospinning proved to be uniquely well suited for biofabrication, resolving several key challenges that are unachievable with current approaches, such as biomolecule preservation, maintenance of source material properties, and the development of extracellular matrix analogs with biomimetic mechanical properties.

Similarly, traditional 3D printing has been modernized and tailored for biofabrication, with the development of bioinks[61,77–79] *in lieu* of the heated printing filament based on synthetic polymers, which renders biological materials inactive. Interestingly, and perhaps not so surprising, natural materials, such as alginate (Figure 4), can better preserve biomolecules and protect cells during printing, and eliminate the use of harmful solvents altogether. Notably, by combining electrospinning with the flatbed control and solvent-free paradigm of 3D printing, melt electrospinning writing is used to produce scalable, defined nanofiber architectures, effectively reducing polymer waste over conventional methods.[80,81] Recently, 4D bioprinting,[82–84] which includes the time dimension, allows the production of living materials, whereby biofabrication takes place post-templating and provides a dynamic and interactive environment to further tailor fiber formation and textile assembly. The widespread implementation of bioprinting for biotextiles with precise shapes and patterning will minimize the substantial pre-consumer textile waste; given that nearly half of all the fiber entering the fashion value chain becomes waste, throughout the various stages of production, from fiber to yarn, fabric, and garment.[85]

The eco-conscious biofabrication technologies highlighted here are uniquely positioned to tailor bioengineered textile fibers across length scales. Importantly, green manufacturing production of bioengineered materials is directly aligned with the canonical principles of green chemistry, and by reducing synthesis hazards and material waste, it is designed for inherently safer chemistry and a circular economy.

CONCLUSION AND FUTURE OUTLOOK

Current linear manufacturing and consumption practices of industrial materials, especially fibers and textiles, are not sustainable. However, a host of bioengineering strategies can be implemented to transition from the current linear paradigm to more circular, biocompatible processes. These approaches span from the nanoscale to the macroscale. Recent efforts have shown that nanocellulose pellicle-forming bacteria can be co-cultured with genetically engineered yeasts to incorporate enzymatically produced color.[86] Additionally, processing of these pellicles into leather-like materials via green bioprocessing treatments has been demonstrated.[41] Green manufacturing methods have also been implemented in electrospinning, spanning the micro- and nanoscales. Although these advances highlight the potential of biofabricated textile fibers, it is key that these newly engineered bioprocesses are scrutinized to verify that they result in overall lower carbon emissions. Additionally, these processes must ultimately compete for market share with existing technologies; therefore, efforts to decrease biofabrication costs must also be aggressively pursued. We draw inspiration from nature's blueprints and robust regenerative processes and highlight here particularly promising avenues at the nano-, micro-, and macroscale that will enable and advance the biofabrication of textiles for a circular economy.

Over millions of years, organisms have evolved their DNA to build functional protein materials for performance and resilience within an ecological niche. A majority of efforts to engineer protein biopolymers, such as silk, elastin, or curli, has focused on the use of model organisms, such as *E. coli* or *P. pastoris*, to produce these materials.[87] Yet, a wide range of non-model organisms have begun to receive attention for other biomanufacturing purposes (e.g., biofuel production).[88] Therefore, it is likely that an alternate host, or co-cultured hosts, could dramatically improve both the commercial viability of fermentation of raw textile biomaterials and the sustainability of the overall process. For example, genetic engineering of algae for extracellular production of nanocellulose using the metabolic pathways from *G. xylinum* would enable the direct conversion of renewable sunlight to cellulosic fibers.[89] This approach would both improve the sustainability of the processes and dramatically decrease the media costs for fermentation. Critically, the impact of these genetic modifications or altered nutrient conditions on the thermochemical and mechanical properties of the resulting materials should be characterized. The tools of synthetic biology not only have great potential to improve textile fibers at the nanoscale through these biopolymer modifications but also provide a bridge to greener microscale engineering efforts through the introduction of novel binding or cross-linking sites.

In addition to the production of biopolymer building blocks, nature also provides blueprints for creating 3D hierarchical structures with tailored material properties through molecular self-assembly and enzymatic cross-linking. Bioengineering of fibers with enzymes is powerful, but research to improve enzyme activity and stability under industrial processing conditions, as well as to decrease cost, would improve widespread adoption by the textile industry. Enzyme engineering via molecular modeling and directed evolution, combined with an increasing number of commercial cloning vectors and optimized host strains for high-density expression of enzymes on low-cost carbon sources with a simple scale-up process, has promise for their use as green processing agents.[90]

Combining these bioinspired processing strategies with polysaccharide and protein feedstocks sourced from agro-industrial byproducts can minimize and close material loops across the most impactful industries globally. Cellulose agricultural waste alone could provide 250 M tons of fiber annually, enough to meet 2.5 times the current global textile fiber demand.[91,92] Likewise, bacterial nanocellulose can be obtained and purified from food and beverage side streams as raw material for biotextiles, eliminating the cost and environmental impact of microbial fermentation and associated culture media.[41] The use of waste streams also has the potential to decrease the costs of fermentative biofabrication. However, efforts to understand the variability of waste stream inputs and the reproducibility of the subsequent bio-based fiber processing are needed to fully realize their potential to advance a circular economy.

In addition to reusing waste and byproduct streams, the development of more efficient fiber processing, including dope dyeing, in which color is added to the biopolymer dope before extrusion, use of perfluorinated chemical-, formaldehyde-, and metal-free chemicals, and adoption of solvent recycling would further enhance the environmental performance and circularity of the process. At an even larger scale, the use of renewable energy sources for manufacturing should also be implemented for biofabricated textile fibers. Importantly, any stepwise process improvements should be coupled with a complete, third party LCA. We recommend that these assessments are built into environmental performance metrics and industry certifications.

Most excitingly, both startups and established brands are working across the supply chain to implement these opportunities, with encouraging progress in material innovation, which includes the following: Circular System's Agraloop process that transforms agricultural side streams into spinnable biofibers, GALY producing lab-scale cell-cultured cotton at ten times the agricultural rate, conversion of methane waste to biodegradable polyester fibers by Mango Materials, genetic modification of yeast to produce collagen for animal-free leather by Modern Meadow, biofabricated spider silk by Spintex, Spiber, AMSilk, and BOLT Threads (Figure 3C), mycelium textiles by MYCOworks, bacterial dyes by Colorifix (Figure 3D), and biodegradable textile fibers with DNA programmed color and stretch by Werewool. Collectively, the bioengineering approaches described here apply strategic biomimicry across nano-, micro-, and macroscales to diversify and expand the range of material processes and waste-to-resource approaches to accelerate a paradigm shift to a sustainable circular economy, with enormous potential economic and environmental benefit at scale.

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AUTHOR CONTRIBUTIONS

A.C.O., T.N.S., and H.H.L. wrote the manuscript, and it was edited by all co-authors.

DECLARATION OF INTERESTS

T.N.S., C.L.L., and V.G. are co-founders of Werewool. T.N.S., C.L.L., V.G., C.Z.M., Y.Z., H.H.L., and A.C.O. are co-inventors on a patent application on biodegradable fibers with inherent color. T.N.S. and H.H.L. are co-inventors on a patent application on the biofabrication of microbial cellulose textiles.

REFERENCES

1. World Economic Forum (2014). Towards the circular economy: accelerating the scale-up across global supply chains. http://wef.ch/1rvDRDL.
2. Ellen MacArthur Foundation (2012). Towards the circular economy: economic and business rationale for an accelerated transition. https://www.greengrowthknowledge.org/research/towards-circular-economy-economic-and-business-rationale-accelerated-transition.
3. Fagnani, D.E., Tami, J.L., Copley, G., Clemons, M.N., Getzler, Y.D.Y.L., and McNeil, A.J. (2021). 100th Anniversary of Macromolecular Science Viewpoint: redefining Sustainable Polymers. ACS Macro Lett *10*, 41–53.
4. Vogt, B.D., Stokes, K.K., and Kumar, S.K. (2021). Why is recycling of postconsumer plastics so challenging? ACS Appl. Polym. Mater. *3*, 4325–4346.
5. Christensen, P.R., Scheuermann, A.M., Loeffler, K.E., and Helms, B.A. (2019). Closed-loop recycling of plastics enabled by dynamic covalent diketoenamine bonds. Nat. Chem. *11*, 442–448.
6. Coates, G.W., and Getzler, Y.D.Y.L. (2020). Chemical recycling to monomer for an ideal, circular polymer economy. Nat. Rev. Mater. *5*, 501–516.
7. Vora, N., Christensen, P.R., Demarteau, J., Baral, N.R., Keasling, J.D., Helms, B.A., and Scown, C.D. (2021). Leveling the cost and carbon footprint of circular polymers that are chemically recycled to monomer. Sci. Adv. *7*, eabf0187.
8. Abel, B.A., Snyder, R.L., and Coates, G.W. (2021). Chemically recyclable thermoplastics from reversible-deactivation polymerization of cyclic acetals. Science *373*, 783–789.
9. Altieri, M.A. (1998). Ecological impacts of industrial agriculture and the possibilities for truly sustainable farming. Mon. Rev. *50*, 60–71.
10. S.S. Muthu, ed. (2020). Assessing the Environmental Impact of Textiles and the Clothing Supply Chain, Second Edition (Woodhead Publishing).
11. Quantis Measuring fashion (2018). insights from the environmental impact of the global apparel and footwear industries. https://quantis-intl.com/report/measuring-fashion-report/.
12. World Bank (2018). The Bangladesh responsible sourcing initiative: a new model for green growth. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/614901468768707543/The-Bangladesh-Responsible-Sourcing-Initiative-A-new-model-for-green-growth.
13. Institution of Mechanical Engineers (2018). Engineering out fashion waste. https://www.imeche.org/policy-and-press/reports/detail/engineering-out-fashion-waste.
14. Reineke, J.J., Cho, D.Y., Dingle, Y.T., Morello, A.P., Jacob, J., Thanos, C.G., and Mathiowitz, E. (2013). Unique insights into the intestinal absorption, transit, and subsequent biodistribution of polymer-derived microspheres. Proc. Natl. Acad. Sci. USA *110*, 13803–13808.
15. (2015). https://www.ellenmacarthurfoundation.org/publications/a-new-textiles-economy-redesigning-fashions-future.
16. European Food Safety Authority (2016). Presence of microplastics and nanoplastics in food, with particular focus on seafood. https://www.efsa.europa.eu/en/efsajournal/pub/4501.
17. Deng, Y., Zhang, Y., Lemos, B., and Ren, H. (2017). Tissue accumulation of microplastics in mice and biomarker responses suggest widespread health risks of exposure. Sci. Rep. *7*, 46687.
18. Wright, S.L., and Kelly, F.J. (2017). Plastic and human health: A micro issue? Environ. Sci. Technol. *51*, 6634–6647.
19. Ragusa, A., Svelato, A., Santacroce, C., Catalano, P., Notarstefano, V., Carnevali, O., Papa, F., Rongioletti, M.C.A., Baiocco, F., Draghi, S., et al. (2021). Plasticenta: first evidence of microplastics in human placenta. Environ. Int. *146*, 106274.
20. Levy, B.S., and Patz, J.A. (2015). Climate change, human rights, and social justice. Ann. Glob. Health *81*, 310–322.
21. Sanderman, J., Hengl, T., and Fiske, G.J. (2017). Soil carbon debt of 12,000 years of human land use. Proc. Natl. Acad. Sci. USA *114*, 9575–9580.
22. Bossio, D.A., Cook-Patton, S.C., Ellis, P.W., Fargione, J., Sanderman, J., Smith, P., Wood, S., Zomer, R.J., von Unger, M., Emmer, I.M., and Griscom, B.W. (2020). The role of soil carbon in natural climate solutions. Nat Sustain *3*, 391–398.
23. Kim, D.-S., Kim, Y.-W., Kim, K.-J., and Shin, H.-J. (2017). Research trend and product development potential of fungal mycelium-based composite materials. ksbbj *32*, 174–178.
24. Forgacs, G., Marga, F., and Jakab, K. (2013). Engineered leather and methods of manufacture thereof. US patent US 2013/0255003 A1, filed March 28, 2013, and published, October 3, 2013.
25. Mosher, C.Z., Brudnicki, P.A.P., Gong, Z., Childs, H.R., Lee, S.W., Antrobus, R.M., Fang, E.C., Schiros, T.N., and Lu, H.H. (2021). Green electrospinning for biomaterials and biofabrication. Biofabrication *13*, 035049.
26. OECD (2011). Report on industrial biotechnology and climate change: opportunities and challenges. https://www.oecd.org/sti/emerging-tech/reportonindustrialbiotechnologyandclimatechangeopportunitiesandchallenges.htm.
27. Way, J.C., Collins, J.J., Keasling, J.D., and Silver, P.A. (2014). Integrating biological redesign: where synthetic biology came from and where it needs to go. Cell *157*, 151–161.
28. Qian, Z.G., Pan, F., and Xia, X.X. (2020). Synthetic biology for protein-based materials. Curr. Opin. Biotechnol. *65*, 197–204.
29. Yadav, V., Paniliatis, B.J., Shi, H., Lee, K., Cebe, P., and Kaplan, D.L. (2010). Novel in vivo-degradable cellulose-chitin copolymer from metabolically engineered Gluconacetobacter xylinus. Appl. Environ. Microbiol. *76*, 6257–6265.
30. Fang, J., Kawano, S., Tajima, K., and Kondo, T. (2015). In vivo curdlan/cellulose bionanocomposite synthesis by genetically modified Gluconacetobacter xylinus. Biomacromolecules *16*, 3154–3160.
31. Choi, S.Y., Rhie, M.N., Kim, H.T., Joo, J.C., Cho, I.J., Son, J., Jo, S.Y., Sohn, Y.J., Baritugo, K.A., Pyo, J., et al. (2020). Metabolic engineering for the synthesis of polyesters: A 100-year journey from polyhydroxyalkanoates to non-natural microbial polyesters. Metab. Eng. *58*, 47–81.
32. Breslauer, D.N. (2020). Recombinant protein polymers: a coming wave of personal care

ingredients. ACS Biomater. Sci. Eng. *6*, 5980–5986.

33. Lambert, T.J. (2019). FPbase: a community-editable fluorescent protein database. Nat. Methods *16*, 277–278.

34. Bevis, B.J., and Glick, B.S. (2002). Rapidly maturing variants of the Discosoma red fluorescent protein (DsRed). Nat. Biotechnol. *20*, 83–87.

35. Xia, X.X., Qian, Z.G., Ki, C.S., Park, Y.H., Kaplan, D.L., and Lee, S.Y. (2010). Native-sized recombinant spider silk protein produced in metabolically engineered Escherichia coli results in a strong fiber. Proc. Natl. Acad. Sci. USA *107*, 14059–14063.

36. McDaniel, J.R., MacKay, J.A., Quiroz, F.G., and Chilkoti, A. (2010). Recursive directional ligation by plasmid reconstruction allows rapid and seamless cloning of oligomeric genes. Biomacromolecules *11*, 944–952.

37. Haider, M., Leung, V., Ferrari, F., Crissman, J., Powell, J., Cappello, J., and Ghandehari, H. (2005). Molecular engineering of silk-elastinlike polymers for matrix-mediated gene delivery: biosynthesis and characterization. Mol. Pharm. *2*, 139–150.

38. Amiram, M., Quiroz, F.G., Callahan, D.J., and Chilkoti, A. (2011). A highly parallel method for synthesizing DNA repeats enables the discovery of 'smart' protein polymers. Nat. Mater. *10*, 141–148.

39. Florea, M., Hagemann, H., Santosa, G., Abbott, J., Micklem, C.N., Spencer-Milnes, X., de Arroyo Garcia, L., Paschou, D., Lazenbatt, C., Kong, D., et al. (2016). Engineering control of bacterial cellulose production using a genetic toolkit and a new cellulose-producing strain. Proc. Natl. Acad. Sci. USA *113*, E3431–E3440.

40. Billington, S.L., Criddle, C.S., Frank, C.W., Morse, M.C., Christian, S.J., and Pieja, A.J. (2008). Bacterial poly(hydroxy alkanoate) polymer and natural fiber composites. US Patent US 7,887,893 B2, filed December 12, 2007, and granted February 15, 2011.

41. Schiros, T.N., Antrobus, R., Farias, D., Chiu, Y.-T., Joseph, C.T., Esdaille, S., Sanchiricco, G.K., Miquelon, G., An, D., Russell, S.T., et al. (2021). Microbial biotextiles for a circular materials economy. bioRxiv. https://doi.org/10.1101/2021.09.22.461422.

42. Chen, G.Q. (2009). A microbial polyhydroxyalkanoates (PHA) based bio- and materials industry. Chem. Soc. Rev. *38*, 2434–2446.

43. Chen, G.Q., and Jiang, X.R. (2017). Engineering bacteria for enhanced polyhydroxyalkanoates (PHA) biosynthesis. Synth. Syst. Biotechnol. *2*, 192–197.

44. Buldum, G., Bismarck, A., and Mantalaris, A. (2018). Recombinant biosynthesis of bacterial cellulose in genetically modified Escherichia coli. Bioprocess Biosyst. Eng. *41*, 265–279.

45. Chien, L.J., Chen, H.T., Yang, P.F., and Lee, C.K. (2006). Enhancement of cellulose pellicle production by constitutively expressing Vitreoscilla hemoglobin in Acetobacter xylinum. Biotechnol. Prog. *22*, 1598–1603.

46. Gwon, H., Park, K., Chung, S.C., Kim, R.H., Kang, J.K., Ji, S.M., Kim, N.J., Lee, S., Ku, J.-H., Do, E.C., et al. (2019). A safe and sustainable bacterial cellulose nanofiber separator for lithium rechargeable batteries. Proc. Natl. Acad. Sci. USA *116*, 19288–19293.

47. Bueno, L.L., Elbl, P.M., and Luz, L.S.D.S. (2020). Compositions and methods for plant cell culture. WO/2020/237223, filed 22 May, 2020, and published, 26 November, 2020.

48. Turner, B., Wray, L., Widmaier, D.M., Breslauer, D.N., and Kittleson, J. (2018). Methods and compositions for synthesizing improved silk fibers. US patent application 20180273693 A1, filed March 17, 2016, and published September 27, 2018.

49. Zhu, S.-W., Gao, P., Sun, J.-S., Wang, H.-H., Luo, X.-M., Jiao, M.-Y., Wang, Z.-Y., and Xia, G.-X. (2006). Genetic transformation of green-colored cotton. In Vitro Cell. Dev. Biol. Plant *42*, 439–444.

50. Sun, J., Sun, Y., and Zhu, Q.H. (2021). Breeding next-generation naturally colored cotton. Trends Plant Sci *26*, 539–542.

51. Shibazaki, H., Kuga, S., Onabe, F., and Usuda, M. (1993). Bacterial cellulose membrane as separation medium. J. Appl. Polym. Sci. *50*, 965–969.

52. Jozala, A.F., de Lencastre-Novaes, L.C., Lopes, A.M., de Carvalho Santos-Ebinuma, V., Mazzola, P.G., Pessoa, A., Grotto, D., Gerenutti, M., and Chaud, M.V. (2016). Bacterial nanocellulose production and application: a 10-year overview. Appl. Microbiol. Biotechnol. *100*, 2063–2072.

53. Kabir, S.M.M., and Koh, J. (2021). Sustainable textile processing by enzyme applications (IntechOpen). https://www.intechopen.com/online-first/76122.

54. Duarte, L., Matte, C.R., Bizarro, C.V., and Ayub, M.A.Z. (2019). Review transglutaminases: part II-industrial applications in food, biotechnology, textiles and leather products. World J. Microbiol. Biotechnol. *36*, 11.

55. Deweid, L., Avrutina, O., and Kolmar, H. (2019). Microbial transglutaminase for biotechnological and biomedical engineering. Biol. Chem. *400*, 257–274.

56. Tesfaw, A., and Assefa, F. (2014). Applications of transglutaminase in textile, wool, and leather processing. Int. J. Text. Sci. *3*, 64–69.

57. Kamiya, N., Takazawa, T., Tanaka, T., Ueda, H., and Nagamune, T. (2003). Site-specific cross-linking of functional proteins by transglutamination. Enzyme Microb. Technol. *33*, 492–496.

58. Lee, E.J., Kasper, F.K., and Mikos, A.G. (2014). Biomaterials for tissue engineering. Ann. Biomed. Eng. *42*, 323–337.

59. Wang, J.H., Tang, M.Z., Yu, X.T., Xu, C.M., Yang, H.M., and Tang, J.B. (2019). Site-specific, covalent immobilization of an engineered enterokinase onto magnetic nanoparticles through transglutaminase-catalyzed bioconjugation. Colloids Surf. B Biointerfaces *177*, 506–511.

60. Schiros, T., Lee, C.L., Kattermann, M., Gomez, V., Brudnicki, P., Mosher, C., Antrobus, R., Zhu, Y., Lu, H.H., and Obermeyer, A.C. Biodegradable fibers with inherent color and properties. US patent WO/2021/195257, filed March 24, 2021, and published September 20, 2021.

61. Moroni, L., Burdick, J.A., Highley, C., Lee, S.J., Morimoto, Y., Takeuchi, S., and Yoo, J.J. (2018). Biofabrication strategies for 3D in vitro models and regenerative medicine. Nat. Rev. Mater. *3*, 21–37.

62. Moroni, L., Boland, T., Burdick, J.A., De Maria, C., Derby, B., Forgacs, G., Groll, J., Li, Q., Malda, J., Mironov, V.A., et al. (2018). Biofabrication: a Guide to Technology and Terminology. Trends Biotechnol *36*, 384–402.

63. Castro-Aguirre, E., Iñiguez-Franco, F., Samsudin, H., Fang, X., and Auras, R. (2016). Poly(lactic acid)- mass production, processing, industrial applications, and end of life. Adv. Drug Deliv. Rev. *107*, 333–366.

64. Posen, I.D., Jaramillo, P., Landis, A.E., and Griffin, W.M. (2017). Greenhouse gas mitigation for U.S. plastics production: energy first, feedstocks later. Environ. Res. Lett. *12*, 034024.

65. Posen, I.D., Jaramillo, P., and Griffin, W.M. (2016). Uncertainty in the life cycle greenhouse gas emissions from U.S. Production of three biobased polymer families. Environ. Sci. Technol. *50*, 2846–2858.

66. Reneker, D.H., and Chun, I. (1996). Nanometre diameter fibres of polymer, produced by electrospinning. Nanotechnology *7*, 216–223.

67. Doshi, J., and Reneker, D.H. (1995). Electrospinning process and applications of electrospun fibers. J. Electrostat. *35*, 151–160.

68. Demir, M.M., Yilgor, I., Yilgor, E., and Erman, B. (2002). Electrospinning of polyurethane fibers. Polymer *43*, 3303–3309.

69. Moffat, K.L., Kwei, A.S.-P., Spalazzi, J.P., Doty, S.B., Levine, W.N., and Lu, H.H. (2009). Novel nanofiber-based scaffold for rotator cuff repair and augmentation. Tissue Eng. Part A *15*, 115–126.

70. Erisken, C., Zhang, X., Moffat, K.L., Levine, W.N., and Lu, H.H. (2013). Scaffold fiber diameter regulates human tendon fibroblast growth and differentiation. Tissue Eng. Part A *19*, 519–528.

71. Lee, N.M., Erisken, C., Iskratsch, T., Sheetz, M., Levine, W.N., and Lu, H.H. (2017). Polymer fiber-based models of connective tissue repair and healing. Biomaterials *112*, 303–312.

72. Boushell, M.K., Mosher, C.Z., Suri, G.K., Doty, S.B., Strauss, E.J., Hunziker, E.B., and Lu, H.H. (2019). Polymeric mesh and insulin-like growth factor 1 delivery enhance cell homing and graft-cartilage integration. Ann. N. Y. Acad. Sci. *1442*, 138–152.

73. Qu, D., Zhu, J.P., Childs, H.R., and Lu, H.H. (2019). Nanofiber-based transforming growth factor-β3 release induces fibrochondrogenic differentiation of stem cells. Acta Biomater *93*, 111–122.

74. Lee, S., and Kay Obendorf, S.K. (2006). Developing protective textile materials as barriers to liquid penetration using melt-

electrospinning. J. Appl. Polym. Sci. *102*, 3430–3437.

75. Lu, Y., Xiao, X., Fu, J., Huan, C., Qi, S., Zhan, Y., Zhu, Y., and Xu, G. (2019). Novel smart textile with phase change materials encapsulated core-sheath structure fabricated by coaxial electrospinning. Chem. Eng. J. *355*, 532–539.

76. Liverani, L., Vester, L., and Boccaccini, A.R. (2017). Biomaterials produced via green electrospinning. In Electrospun Biomaterials and Related Technologies, J. Almodovar, ed. (Springer International Publishing), pp. 149–168.

77. Sun, W., Starly, B., Daly, A.C., Burdick, J.A., Groll, J., Skeldon, G., Shu, W., Sakai, Y., Shinohara, M., Nishikawa, M., et al. (2020). The bioprinting roadmap. Biofabrication *12*, 022002.

78. Murphy, S.V., De Coppi, P., and Atala, A. (2020). Opportunities and challenges of translational 3D bioprinting. Nat. Biomed. Eng. *4*, 370–380.

79. Lai, J., Wang, C., and Wang, M. (2021). 3D printing in biomedical engineering: processes, materials, and applications. Appl. Phys. Rev. *8*, 021322.

80. Brown, T.D., Dalton, P.D., and Hutmacher, D.W. (2011). Direct writing by way of melt electrospinning. Adv. Mater. *23*, 5651–5657.

81. Hutmacher, D.W., and Dalton, P.D. (2011). Melt electrospinning. Chem. Asian J. *6*, 44–56.

82. Gladman, A.S., Matsumoto, E.A., Nuzzo, R.G., Mahadevan, L., and Lewis, J.A. (2016). Biomimetic 4D printing. Nat. Mater. *15*, 413–418.

83. Lai, J., Ye, X., Liu, J., Wang, C., Li, J., Wang, X., Ma, M., and Wang, M. (2021). 4D printing of highly printable and shape morphing hydrogels composed of alginate and methylcellulose. Mater. Des. *205*, 109699.

84. González, L.M., Mukhitov, N., and Voigt, C.A. (2020). Resilient living materials built by printing bacterial spores. Nat. Chem. Biol. *16*, 126–133.

85. Reverse, Resources. (2017). https://reverseresources.net/about/white-paper.

86. Gilbert, C., Tang, T.C., Ott, W., Dorr, B.A., Shaw, W.M., Sun, G.L., Lu, T.K., and Ellis, T. (2021). Living materials with programmable functionalities grown from engineered microbial co-cultures. Nat. Mater. *20*, 691–700.

87. Werten, M.W.T., Eggink, G., Cohen Stuart, M.A., and de Wolf, F.A. (2019). Production of protein-based polymers in pichia pastoris. Biotechnol. Adv. *37*, 642–666.

88. Blazeck, J., Hill, A., Liu, L., Knight, R., Miller, J., Pan, A., Otoupal, P., and Alper, H.S. (2014). Harnessing Yarrowia lipolytica lipogenesis to create a platform for lipid and biofuel production. Nat. Commun. *5*, 3131.

89. College of Natural Sciences the University of Texas at Austin (2013). Engineering algae to make the "wonder material" nanocellulose. https://cns.utexas.edu/news/engineering-algae-to-make-the-wonder-material-nanocellulose.

90. Nierstrasz, V., and Cavaco-Paulo, A. (2010). Advances in Textile Biotechnology (Elsevier Science).

91. Biomimicry, Institute. (2020). https://biomimicry.org/thenatureoffashion/.

92. Circular systems. Agraloop BioFibre™: the new natural fiber. https://circularsystems.com/agraloop. Accessed July 13, 2021.