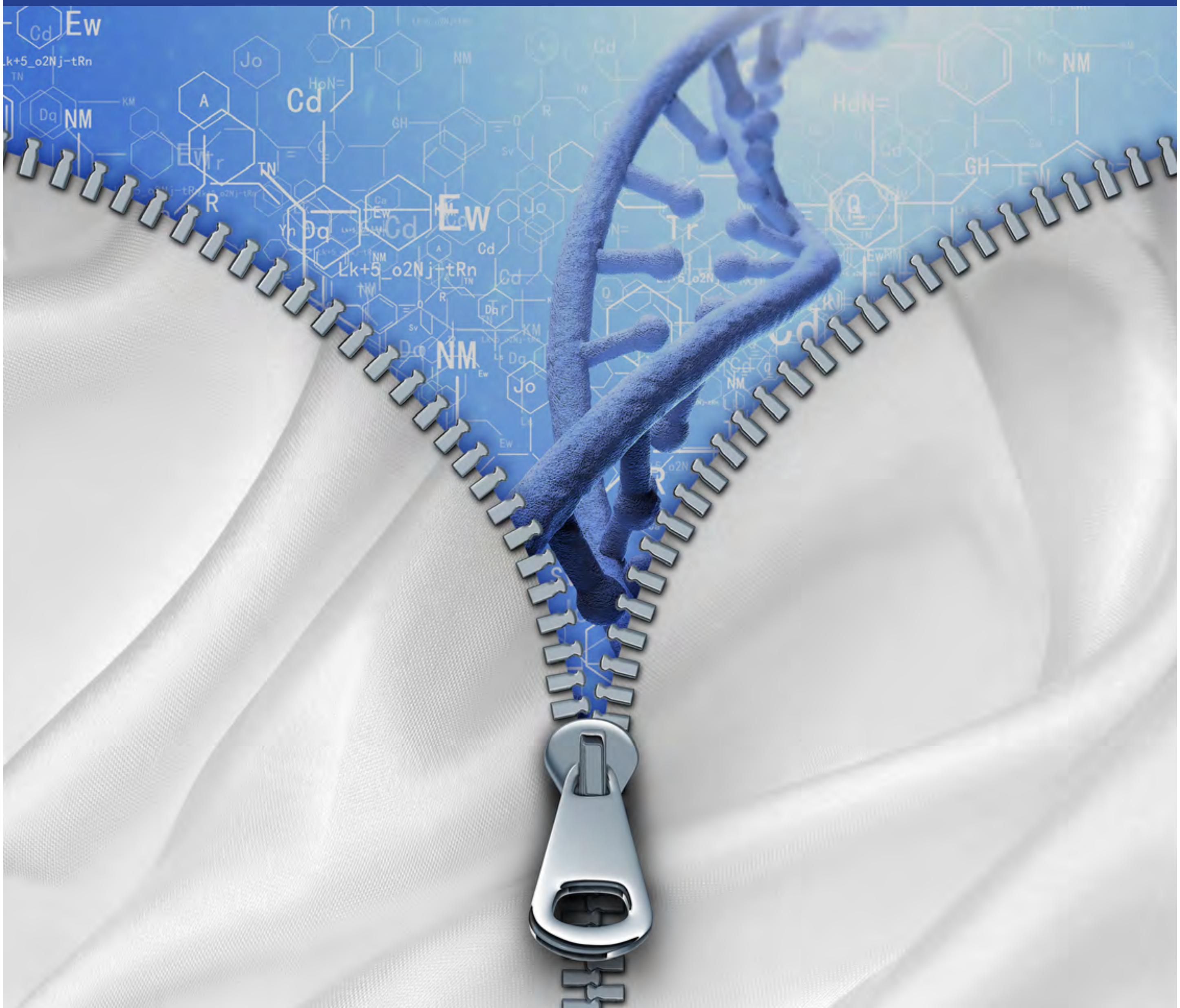
SYNTHETIC BIOLOGY SECTOR STUDIES: **TEXTILES**



GENETICALLY ENGINEERED CLOTHES:

Synthetic Biology's New Spin on Fast Fashion

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tracking technology
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Acknowledgements

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September, 2018

About ETC Group: ETC Group works to address the socioeconomic and ecological issues surrounding new technologies that could have an impact on the world's marginalized people. It operates at the global political level and works closely with partner civil society organizations (CSOs) and social movements, especially in Africa, Asia and Latin America. ETC Group is headquartered in Val David, Canada, and Davao, Philippines, with offices in Mexico City and Guelph, Canada. ETC Group acknowledges support from the Frontier Co-op Giving Fund, The CS Fund and The AgroEcology Fund in our ongoing work on synthetic biology.

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About Fibershed: At Fibershed, we work to develop regional natural fiber systems that generate lasting prosperity for our local economies, stabilize our global climate, while enhancing the health and diversity of our ecosystem. We understand that the way we produce and consume clothing needs to be transformed. Our work is focused upon generating new working models that strike a balance between the intersection of meaningful livelihoods and the protection & regeneration of natural systems.

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Executive Summary

Source: PaigeGreenPhotography

Synthetic biology start-ups and giant chemical companies want to genetically engineer the shirt on your back to grab a piece of the $1.3 trillion retail apparel market.[1]

Synthetic biologists (the next generation of extreme genetic engineers) are using machine-made DNA to engineer microbial cells that can produce novel substances – including biomaterials that can be spun into fibres. The high-tech genetically engineered (GE) fibre future is being sold to eco-conscious consumers as "green" and "sustainable," but it threatens to undermine the livelihoods of millions of natural fibre producers and unleash new environmental hazards.

Fledgling synthetic biology (also known as syn bio) companies like Bolt Threads (US), Spiber, Inc. (Japan) and AMSilk (Germany) tout their high-tech GE fermentation processes as a game changer with the potential to up-end the trillion-dollar textile market.[2] They are engineering microbes (like yeast and bacteria) to secrete proteins that mimic the qualities of spider silk or other natural fibres. Although syn bio companies such as Bolt Threads are now focusing on high-value fibres such as silk, they claim that in time microbes can be engineered to produce synthetic proteins that mimic the performance qualities and properties of virtually any fibre or material – natural or synthetic.[3] The longer-term goal is to converge high-tech fabrics with other technologies – including nanotechnology, 3D printing and electronics – to bring on a "fashion revolution" with clothes that can "see, hear, sense, communicate, store and convert energy, and monitor health."[4]

"Fast fashion" describes an industrial textile economy that is profoundly broken. It is wasteful, polluting and climate-destroying.[5] Fast fashion means disposable, low-quality apparel including those derived primarily from synthetic, fossil-fuel-based polyester (plastic) fibres that are associated with toxic chemicals, outsized carbon footprint and microplastic pollution. Fast fashion also relies on complex, long-distance supply chains and cheap and economically disenfranchised labour. High-tech approaches, including synthetic biology's genetically engineered fibres, don't necessarily put the brakes on fast fashion, and could amplify the most damaging effects of industrial textile production.

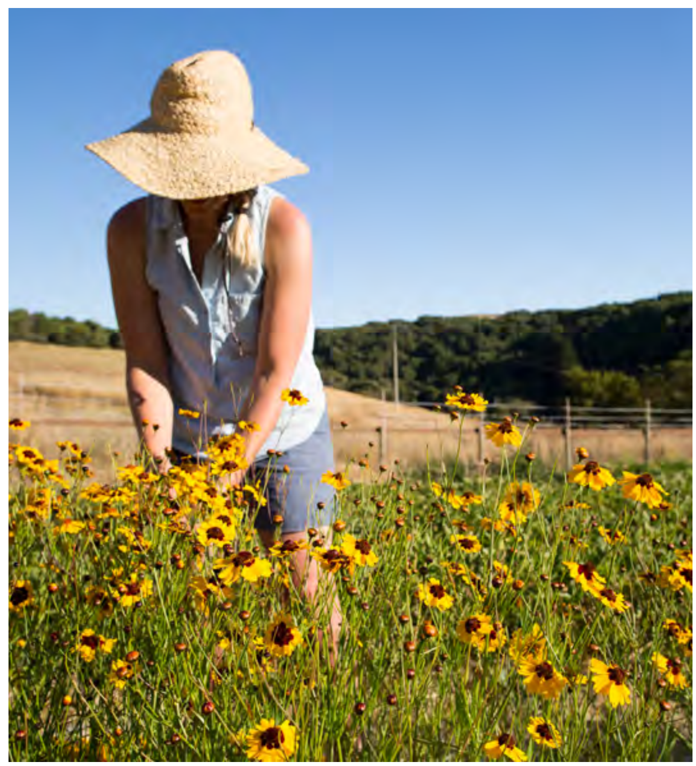
No one yet understands the environmental and health risks posed by the genetically engineered organisms used to produce synthetic biology fibres – including the biological waste from the fermentation process – but that's not stopping synthetic biology companies from touting their novel fibres as sustainable and environmentally benign, and even a techno-fix for the textile industry's dirty, fast fashion. In reality, the payoff of syn bio fibre production is cheaper high-value fibres produced in factory-based fermentation tanks that require fewer workers – all under the green guise of "natural" sustainability.

A closer look reveals that there is nothing natural or sustainable about synthetic biology's high-tech (and potentially high-risk) approach to novel fibre production. Far from the promise of sustainability, the current development of "smart" techno-fibres raises the appalling spectre of amplifying new sources of industrial pollution: Beyond electronic waste (e-waste) and microfibre plastic pollution, synthetic biologists open the door to a new kind of biotech waste (b-waste). Furthermore, if synthetic biologists succeed in enlisting microbial metabolism to mimic silk or other natural fibres on a commercial scale at a competitive price, it could disrupt natural fibre markets and destroy the livelihoods of millions of people who produce and process authentically natural fibres.

We must build an alternative textile economy. Even major textile industry players acknowledge that fast fashion will lead to "potentially catastrophic" outcomes: the status quo is not an option.[6] The good news is that sustainable fibres are already all around us: plant and animal-based natural fibres are 100% biodegradable, renewable and they support the livelihoods of millions of rural communities worldwide.

Natural fibres as they are produced today are not a one-size-fits-all panacea for the world's apparel/textile needs, especially when it comes to chemical and water intensive production of conventional cotton. Around the world, a growing movement of fibre producers, processors and workers are building (or in some regions, re-building) regional and regenerative textile economies based on the creation of place-based textiles (known as fibersheds). Fibersheds are designed to create lasting ecological and economic prosperity via the creation of cooperatively-based direct markets.[7] Fibershed systems foster economic development through livelihood creation, and by supporting and creating farming systems grounded in ecologically-enhancing forms of agriculture.

Increasing sustainable fibre options – and securing support for those options – is imperative. Evaluation of novel fibre technologies must go beyond a narrow technical risk/benefit evaluation to include a broader, participatory technology assessment. It will require a system-wide lifecycle approach that considers all phases of fibre production, consumption and disposal, including a full assessment of the social and economic impacts of new fibre technologies. A new textile economy must feed farmers and workers, restore natural systems, and build sustainable communities.



Farmer harvesting coreopsis flowers for dye. Source: PaigeGreenPhotography

This report examines current efforts to harness synthetic biology to produce high-tech fibres, cuts through the jargon, unravels industry hype and highlights the solutions that are our best hope for an authentically sustainable textile economy.

Introduction: Synthetic Biology as a New Production Platform

Genetic engineering is changing. Nearly two generations of consumers have been buying the products of 'conventional' genetically engineered fibres (i.e., genetically modified cotton) – whether they knew it or not. Now a new industrial platform involving more "extreme" genetic engineering has entered the market place – whether we want it or not.

What is Synthetic Biology? Synthetic biology (syn bio) can refer to various bioengineering techniques that involve the digital design of genetic systems using machine-made DNA. The current ascendant application of syn bio is to, in effect, turn microbes (like yeasts and common bacteria) into "living factories"[8] that can be "retrofit" at will to produce a desired end product. Synthetic biologists engineer and construct "metabolic pathways" that are inserted into microorganisms. When the altered microorganisms are given a carbon-based food such as glucose from corn or sugarcane, the metabolic pathway can produce a valuable compound as a by-product. More than a decade ago, ETC Group called synthetic biology "genetic engineering on steroids."[9] Now biotechnology is converging with automation technologies including machine-made DNA, nanotechnology, robotics, data mining and artificial intelligence and making it possible to manipulate existing organisms and design entirely new ones at an ever-increasing scale and pace. One synthetic biology company describes this burgeoning industry as the "directed creation of genetic diversity."[10]

The use of natural strains of microbes for industrial purposes has a long history. Commercial-scale fermentation to make yogurt is a familiar example: specific species of bacteria are fed milk, they eat the sugars in the milk (lactose) and produce a compound called lactic acid, which thickens the milk and sours its taste. However, when an engineered, artificial metabolic pathway is inserted into a microbe, the fermentation process can alter both the feedstock and the by-product so that the microbe produces a compound it would never have produced on its own. This process is often called synthetic *biosynthesis*. Fuels, pharmaceutical compounds, fragrances, and food ingredients can be artificially biosynthesized using synthetic biology techniques. Scaling such biosynthesis up to commercial volumes has so far been technically challenging (producing biofuels via synthetic biology failed largely because the process was hard to scale[11]). Because of this, most current synthetic biosynthesis research and development (R&D) is focused on producing high-value, low-volume compounds that can replace those that have been traditionally botanically sourced.[12] However, other products of synthetic biosynthesis are beginning to gain attention and investment, including a renewed focus on materials.

In some contexts, the commercial success of an artificially biosynthesized material will depend on its performance and cost – for example, coatings used in surgery that could prove more durable and biocompatible than the industry standard, or geotextiles that could keep soils in place rather than sliding onto roadways. With other consumer products, performance and cost may still matter, but the product's "story" could be equally consequential. Right now, a handful of companies in the apparel sector have begun to fabricate and market a story of high-tech biosynthesized textiles as high-performance, eco-friendly and fashionably sustainable.

Why Are High-Tech Fibre Companies Pursuing the Synthetic Biology Platform?

The synthetic biology platform offers three major theoretical "advantages" to the fast fashion industry:

» **Factory-based fermentation platforms offer the potential to secure cheaper, more uniform, stable and accessible sources of raw materials and products.** In theory, factory-based fermentation would require fewer workers and slash labour costs. Fibre companies would no longer face the logistical complexity of sourcing materials from farmers or other suppliers in remote locations. In the words of one syn bio company's promotional literature, the technology promises to solve "the supply chain issues of nature" including "lack of convenience factors."[13]

» **The ability to claim biosynthesized fibres as "natural" and "eco-friendly" products.** Synthetic biology companies assert that biosynthesized fibres manufactured via microbial fermentation are "nature-identical"[14] to the naturally-derived version, and therefore do not require new regulatory oversight and assessment. There is growing appeal for "eco-fibres" or "sustainable fashion" – despite the murkiness that surrounds these terms.[15]

» **Buying into sci-fi trends.** Furthermore, synthetic biology start-ups may hope to capitalize from the glitz of high-tech, ultra-hip fashion – from 3D printed clothing to superhero-evoking spider silk to "aerospace-tech dress shirts."[16]

» **With the ability to engineer organisms that don't exist in nature there is potential to manufacture made-to-order fibres with technical qualities that out-perform both existing natural and synthetic fibres.** In theory, syn bio companies could improve and customize fibre/material products, all of which will be proprietary. Both the synthetic microbes and the resulting protein fibres/materials are typically protected by a web of exclusive monopoly patents. For syn bio companies, the appeal of "biocontainment" in industrial fermentation facilities isn't just about biosafety; it may have more to do with building walls around proprietary microbes and products.

Ready-to-Wear Microbes? Fashion Meets the New Materials Science

While some synthetic biology companies are developing performance biomaterials for outdoor technical sports and military applications, others are hoping to entice technophile, 'eco-conscious' and affluent consumers in the fashion apparel market.

DuPont First Over the Bridge: The pioneer of biosynthesized fibre production for the textile/apparel market is the US chemical colossus DuPont (now DowDuPont). DuPont was one of the first companies to enter the fermentation-derived biomaterial market with its bio-synthesized version of a compound called 1,3 propanediol (PDO), a main ingredient in some kinds of plastics. PDO was discovered in DuPont's labs back in the early 1940s, but was shelved because it was too expensive to produce.[17] A half-century later, using metabolic pathway engineering technology from Genencor (now a subsidiary of DowDuPont), "Bio-PDO" was developed over a seven-year period, followed by commercial-scale production through a joint venture between DuPont and the sugar king Tate & Lyle.[18]

Today Bio-PDO is churned out by "highly engineered"[19] and patented *E. coli* bacteria (engineered with more than 40 genetic changes), which eat up glucose from corn sugars. The Bio-PDO is shipped from the production facility in Tennessee to different factories (one is in North Carolina and another in China) where it's mixed with a petroleum-based compound called terephthalic acid (TPA) and made into plastic pellets.[20]

DuPont's Bio-PDO/TPA polymer is called Sorona and has been in commercial production for more than a decade. Carpets were Sorona's first textile application. Now Sorona is prominently used in the apparel sector, blended with natural and other synthetic fabrics. According to DuPont, apparel brands including Izod, Timberland, Calvin Klein Golf and Spun Bamboo use Sorona fibres in their product lines.[21] More recently, outdoor apparel companies L. L. Bean, Royal Robbins, The North Face and Anta have added Sorona blends to some of their apparel offerings. Unifi, a US-based company turning post-consumer plastic bottles into fibre for clothing, recently announced a collaboration with DuPont Sorona to develop insulation for cold weather outer wear.[22]

Source: Alibaba

Sorona's Success Story – Greenwashing the Textile/Fibre Industry: There is no denying that DuPont's Sorona is a commercial and public relations success. Before it was even on the market, Sorona earned DuPont the Presidential Green Chemistry Award (2003)[23] and in 2017, market research firm Frost & Sullivan named DuPont the European Bio-based Materials Company of the Year. Frost & Sullivan explained that Sorona "demonstrates the company's commitment to implementing innovative practices that lower reliance on fossil fuels and elevate product quality and manufacturing efficiency."[24] DuPont recently announced a second expansion of its Bio-PDO factory in Tennessee since its first expansion in 2010. It aims to increase annual production by 17,500 tons,[25] in comparison with its current annual production of about 64,000 tons.[26]

Despite DuPont's successful promotion of Sorona as a green, eco-friendly alternative to fossil fuel-based synthetic fibres, Sorona shares some of the same environmental drawbacks with conventional polyester. Sorona contains at most 37% of renewably-sourced Bio-PDO – the rest is petroleum-derived TPA. Also, Sorona is neither biodegradable nor compostable, thus contributing to microplastics pollution (see below).[27] Sorona, made from industrially grown corn starch, is also implicated in the negative environmental impacts of chemical-intensive, mono-crop agriculture.[28]

Producing Sorona requires land and water for growing the genetically modified corn used as feedstock, which competes with food production and relies on intensive herbicide use.[29] Virtually every syn bio company, including DuPont, claims it will one day be able to use "wasted" biomass to not compete with food production, or even use captured greenhouse gases as feedstocks in microbial bio-production. DuPont's ubiquitous claim that Sorona "uses 30% less energy and releases 63% fewer greenhouse gas emissions than conventional nylon made from petroleum"[30] is impressive only when compared to the horrific environmental impacts of conventional, petroleum-based synthetic fibre production. It doesn't fare so well when evaluated against natural fibres (see below).

Additionally, the fermentation process that produces DuPont's Sorona bio-ingredient creates not only CO_2 but also waste – currently about 12,000 tons of "spent microbial biomass" (SMB) annually from its Tennessee production facility, which is shipped to landfills for disposal.[31] In conventional fermentation-based industries such as beer-making, SMB is used in agricultural production as feed or fertilizer. Because DuPont's microbes have been extensively genetically engineered, its SMB hasn't been used in agriculture "due to concerns over horizontal gene transfer."[32] DuPont would like to change that: the company has commissioned at least two research studies exploring the safety and efficacy of using its SMB on soils as a source of nitrogen for crops. If allowed, DuPont's disposal of SMB on farmers' fields would create an additional revenue stream while enabling the company to tout its re-use/recycling of bio-waste.[33]

From a biotech industry viewpoint, DuPont's most enviable successes to date have been its ability to scale-up its syn bio bacterial fermentation *and* to sell Sorona's questionable 'eco-friendly' story to affluent and eco-conscious consumers.

A Model Marvel – Microbial Production of Silk-Like Proteins

With Sorona, DuPont commercialized a polyester fibre partially produced via syn bio fermentation and forged a path for a partially biosynthesized product to enter the synthetic textile industry – but it is still plastic fibre. Other companies aim to biosynthesize fibres that more closely replicate the properties of high-value natural fibres. Still others are using the syn bio fermentation platform to insert machine-made, recombinant DNA into microbes to get them to churn out "spider silk-like proteins" when they metabolize sugars.[34] The proteins can then be spun into fibres that, theoretically, match the texture, strength, elasticity and biodegradability of spiders' dragline silk.

Why create a biosynthetic silk? Due to its unique mechanical properties of both strength and elasticity – and its apparent biocompatibility[35] – spider silk is being considered for use in medicine as a new biomaterial for drug delivery and tendon and ligament replacement/repair. Biosynthesized spider "silk-like proteins"[36] are also being targeted for use in high fashion, athletic gear, 3D printing (to be mixed with thermoplastics to increase strength and decrease weight)[37] and military gear. Some demonstration-scale apparel has been produced using syn bio synthetic spider silk, but just one company has products on the market: Germany's AMSilk sells its "Biosteel" fibres as coatings for medical implants[38] – arguably not as flashy as the proof-of-concept "Futurecraft Biofabric" shoes the company unveiled in late 2016 with corporate partner Adidas.[39] AMSilk also sells its spider silk-like proteins in powder form to cosmetics companies for use in high-end skin lotions.[40] (Medical device and personal-care ingredient applications imply lower volume production than apparel does, which is significant because cost-effective scale up, including securing feedstocks, continues to pose a daunting challenge across the syn bio industry.)

Is it really "spider silk"?

Future commercial sellers of biosynthesized fibres advertised as 'spider silk' may find themselves entering a legal grey zone. While the 'spider' tag lends marketing cred, the reality is that the bioengineered fibres do not come from spiders but from a genetically engineered microorganism. Calling this 'silk' may also raise concerns from natural silk producers. The synthetic fibres Rayon and Nylon were both originally presented as a silk alternative, but we would never call it 'silk' today.

In the world of food products, consumer actions and other lawsuits have been brought for misuse of words such as "natural," or misleadingly labelling artificial substitutes as 'milk,' 'meat' or 'mayonnaise.' Labelling genetically engineered protein from a yeast or bacteria 'spider' or 'silk' may also be viewed by consumers as misleading, especially if it is not clearly communicated that they are from a bioengineered source.

Additionally, the actual engineered proteins produced by, for example, Bolt Threads' bioengineered yeast may in fact be novel proteins not previously found in nature that are functionally and physically different from actual naturally-derived spider silk proteins.[41] Bolt Threads explains that they use spider silk proteins as "inspiration" for their engineered proteins but that they intend to adapt the properties of the proteins to match market needs (e.g. strength, elasticity, waterproof). Even the DNA of the engineered microorganisms is not directly taken from spiders. Bolt says on its website that, "We look at the DNA of spiders and then create sequences engineered for product performance. The whole process is informed by our understanding of how spiders make silks."[42]

Bolt Threads microsilk tie label (Source: tevonews.com). It may be that the only claim on this label that is technically correct is that Bolt Threads products are made in Emeryville CA. A more truthful label might read "100% bioengineered fibre protein, made by yeast in Emeryville, CA."

...[C]onsumer apparel...speaks so closely to our own personal identity — how we look every day, how we present to others... Young people and affluent people care deeply and will pay for sustainability. And if you're any brand on this planet...I bet they would love to have the demographics of young and affluent, like those sound like pretty good ones to me.

—Dan Widmaier, co-founder of Bolt Threads, speaking on the "Loose Threads" podcast, 31 October 2017.

Cotton in flower. Source: PaigeGreenPhotography

The Bottom Line: We don't know if companies will ultimately succeed in scaling up the biosynthesis of fibres that mimic natural fibres and 'super' natural fibres like spider silk for the apparel market – even within the 'high-value, low-volume' model adopted by other sectors aiming to move toward biosynthesis-based production (e.g., fragrance and food ingredients). We do know, however, that failed technologies can still have a significant market impact – if only by displacing competitors who fear the looming presence of a potentially disruptive technology and opt to exit the marketplace, or by discouraging would-be competitors that conclude the risk is too great to enter the market.[43] ***A very real concern is that the money, hype and scientific brain power being invested in synthetic biology platforms could foreclose opportunities for truly sustainable fibre options.***

Table 1: Companies Using Microbe-Based Biosynthesis for Fibre Manufacturing Targeting the Apparel Sector

Company	Host Microbe, if known	Feedstock, if known	Biosynthesized Product	Location of Fermenter(s), if known
DuPont Industrial Biosciences (unit of DowDuPont), US	Proprietary, recombinant strain of *E. coli*	Corn sugar (dextrose)	Bio-PDO monomer (polymer brand-name Sorona manufactured in Grifton, NC, US and Jiangsu, China)	Loudon, TN, US (adjacent to Tate & Lyle's corn wet mill)
Spiber, Inc., Japan	Proprietary, recombinant strain of *E. coli*	Glucose,[44] source unknown	Fibroin-like protein and silk-like fibres, brand name QMONOS	"Prototyping studio," Tsuruoka, Japan[45]
Bolt Threads, US	Proprietary, recombinant strain of yeast, species unknown	Corn sugar (dextrose)[46]	"Improved silk fibres"[47] branded "microsilk"	Lab in Emeryville, CA, US; partnered with Michigan Biotechnology Institute, Lansing, MI, US (2015)
AMSilk, Germany	Proprietary, recombinant strain of *E. coli*	Glucose, source unknown	"Silk biopolymers," brand name Biosteel	Planegg, Germany
Araknitek, US	Proprietary, recombinant strain of *E. coli* (also uses alfalfa and goats as hosts)	Glucose, source unknown	"Synthetic spider silk" for high-performance fabrics, composite materials, coatings	Synthetic Biomanufacturing Facility, Utah State University, Logan, UT, US (R&D scale)
Korean Advanced Institute of Science and Technology (KAIST), South Korea	Proprietary, recombinant strain of *E. coli*	Glucose, source unknown	"silk-like" protein, "silk-like" fibre[48]	Daejeon, Korea (R&D scale)
Spidey Tek	Bacteria (unclear, likely *E. coli*)	Unclear, likely a recombinant strain of *E. coli*	"real Spider Silk," Arachno	Los Angeles, US

Survival Strategies: With no "spider silk-like," biosynthesized fibres on the apparel market beyond short runs of demonstration pieces, companies currently find themselves in the so-called "valley of death": an R&D phase of post-invention, pre-market in which companies seek investment (e.g., venture capital, government grants) and technical and/or financial partners to remain viable.[49] Keeping investor and consumer enthusiasm alive is crucially important while companies slog through the "valley of death."

A seemingly robust and/or broad intellectual property (IP) portfolio can also help persuade potential investors that a company will be in a strong market position once in the marketplace.[50]

Table 2 below shows examples of IP held by and investment in the "spider silk" start-ups as they hope to successfully navigate the valley of death innovation phase.

Table 2: Biosynthesized "Spider Silk" Fiber Start-ups, Patent Activity, Investment and Corporate Partners

Company	Selected Relevant Intellectual Property	Amount of Capital Raised (Seed, Venture or Grants), Announced (if known)	Corporate Development Partners, Announced (if known)
Spiber, Inc., Japan	WO2017090665A1: Method for producing fibroin-like protein; US9689089 (patent): Solution-dyed protein fiber and method for producing same; US8979992 (patent): Polypeptide solution, artificial polypeptide fiber production method and polypeptide purification method using same	$161 million*	Goldwin, Inc. (The North Face distributor in Japan)
Bolt Threads, USA	WO2016149414A1: Improved Silk Proteins; WO2017214618: Recombinant Protein Fiber Yarns with Improved Properties; WO2015042164A3: Methods and compositions for synthesizing improved silk fibers; US20150293076: Cellular Reprogramming for Product Optimization	$213 million**	Patagonia, Stella McCartney
Araknitek, USA	US20150047532 / WO2015023798A1: Synthetic spider silk protein compositions and methods (Randolph Lewis, Assignee)		
Korean Advanced Institute of Science and Technology (KAIST), South Korea	US20120231499: High-molecular-weight recombinant silk or silk-like protein and micro- or nano-sized spider silk or silk-like fiber produced therefrom		Spiber, Inc.
Inspidere, Netherlands	US20150056256: Method for treatment of spider silk-filament for use as thread or a composition in the manufacture of cosmetic, medical, textile or industrial applications such as bio-artificial cell tissue or skin based on (recombinant) spider silk		

* https://www.spiber.jp/en/archives/category/finance (01.12.2018)

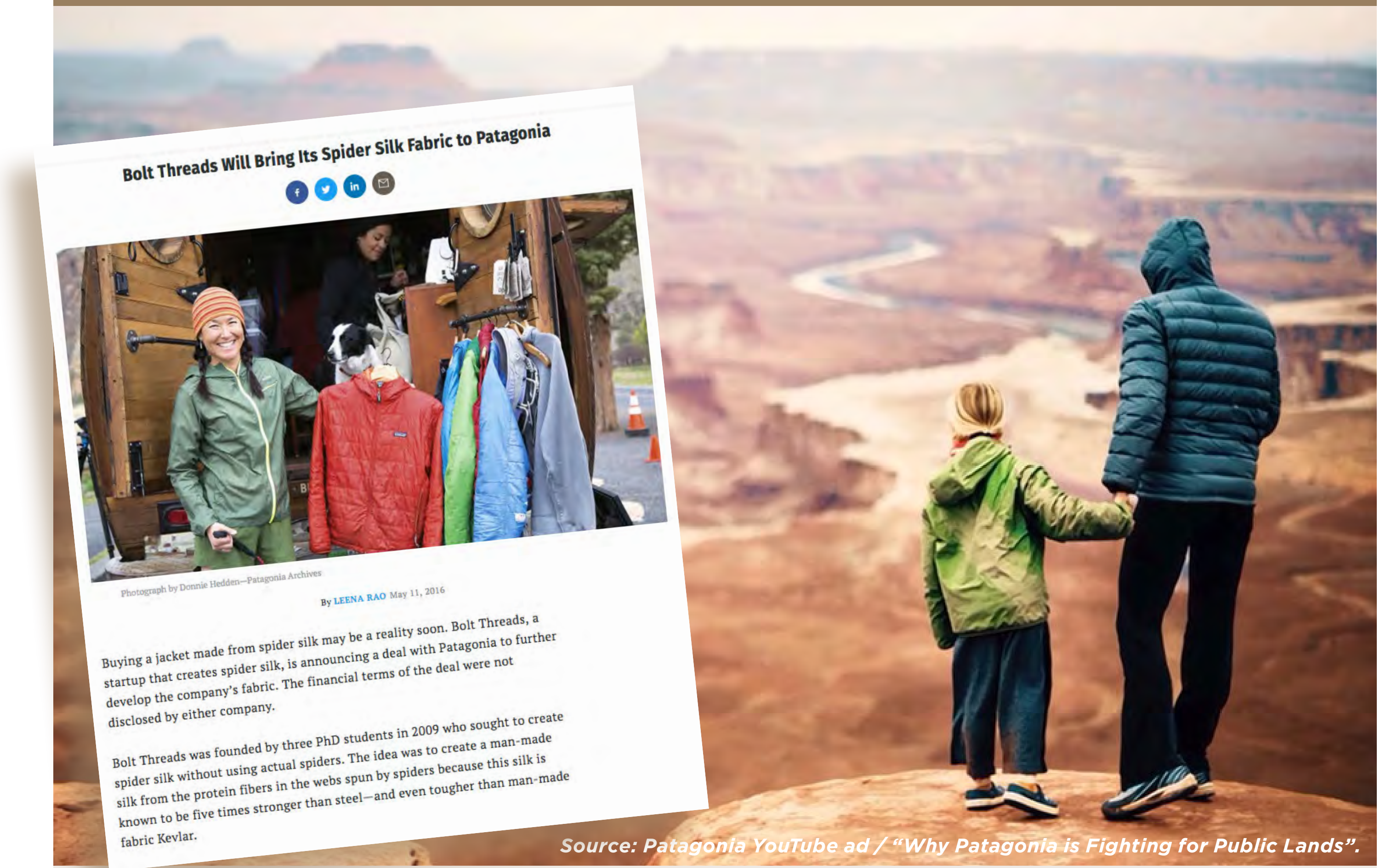
** https://techcrunch.com/2018/01/03/spider-silk-startup-bolt-threads-closes-on-123-million-in-series-d-funding/

Glowing media attention can give fledgling companies a boost. For example, Bolt Threads has successfully pushed the stronger-than-steel-spider silk story, even while acknowledging that its current "spider silk" – still in the demonstration stage – is not especially durable, stretchy or even waterproof.[51] Particularly now, in the era of crowdfunding, the public often serves multiple roles in the product development process – as a gauge of potential consumer interest, as actual investors and, eventually, as consumers. (Two "cellular agriculture" companies developing syn bio meat, for example, have raised almost $400,000 from the public via the crowdfunding website Indiegogo.[52]) In 2017, Bolt Threads held a lottery to select 50 people who were given the opportunity to pay $314 for a "spider silk" tie. Bolt Threads' co-founder and CEO Dan Widmaier presented the lottery as "marking the end of a chapter of this technology where it was all research," as well as "marking the moment where we're ready and able to make cooler products."[53] Lottery winners were announced at the hip SXSW technology/arts conference in Austin, Texas as part of a "stellar marketing strategy," including "star-studded models" and the screening of a video showing Bolt Threads' first spider silk necktie being packaged up to send to Stan Lee, creator of Spider Man, c/o Marvel Comics.[54]

Co-branding – a kind of contagious credibility – can boost investor confidence and help attract new money. Bolt Threads, again, has been successful in hooking up with major players and managed to pull off co-branding wins in both the high fashion and down-to-earth worlds (see box). In 2017, Bolt Threads announced it had entered into a collaboration with Stella McCartney, the eponymous high-fashion design company associated with animal rights activism and sustainability. Stella McCartney used Bolt Threads' biosynthesized silk to create a one-off gold dress that was exhibited at the Museum of Modern Art in New York. In April 2018, Bolt Threads and Stella McCartney unveiled another one-off for a museum exhibit: this one used biosynthesized mycelium from Bolt Threads (using technology licensed from Ecovative) to produce a Stella McCartney "Falabella bag" that will be exhibited at the Victoria & Albert's new London exhibit, "Fashioned from Nature."[55]

Source: Bolt Threads

From Organic Pioneer to Biotech Backer: Patagonia's Eco-Conscious Contradiction



Bolt Threads Will Bring Its Spider Silk Fabric to Patagonia

Photograph by Donnie Hedden—Patagonia Archives

By LEENA RAO May 11, 2016

Buying a jacket made from spider silk may be a reality soon. Bolt Threads, a startup that creates spider silk, is announcing a deal with Patagonia to further develop the company's fabric. The financial terms of the deal were not disclosed by either company.

Bolt Threads was founded by three PhD students in 2009 who sought to create spider silk without using actual spiders. The idea was to create a man-made silk from the protein fibers in the webs spun by spiders because this silk is known to be five times stronger than steel—and even tougher than man-made fabric Kevlar.

Source: Patagonia YouTube ad / "Why Patagonia is Fighting for Public Lands".

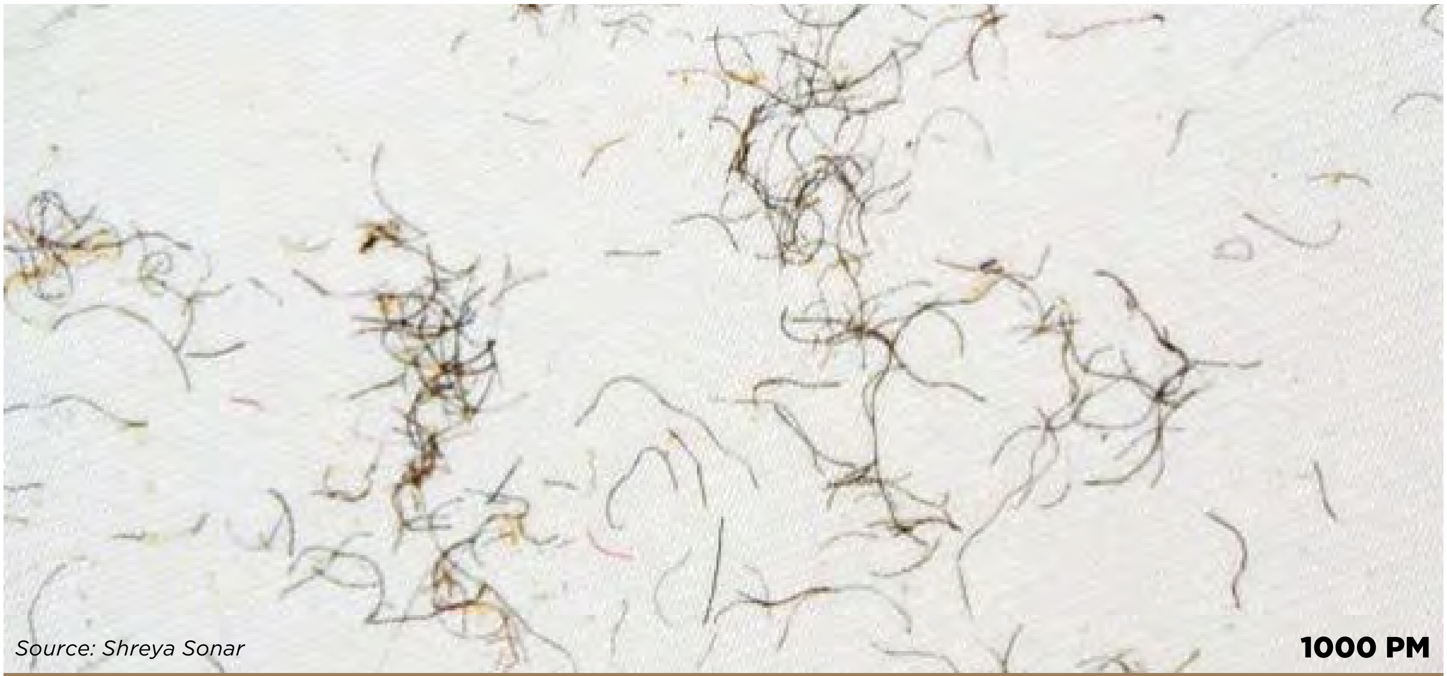
Many consumers perceive US apparel company Patagonia as a socially-responsible company that is committed to environmental sustainability, fair labour practices and supply chain transparency. In the past, Patagonia has deliberately positioned itself as a precautionary anti-GMO (genetically modified organism) brand - supporting initiatives to promote the labelling of GMOs in foods, refusing to sell genetically engineered (GE) cotton, and rejecting PLA, a corn-based fiber made with GE corn feedstocks. In 2002, founder Yvon Chouinard penned a key essay "What does a Clothing Company Know About Genetic Engineering?" and the company subsequently ran campaign ads that argued "Let's not repeat the mistakes we have made in the past with such inadequately tested technologies as DDT and nuclear energy. We don't know enough about the dangers of genetic engineering. Let's find out all the risks before we let genetically modified organisms loose on the world or continue to eat them in our food."[56] Indeed, Patagonia has even gone further to try to position itself as an organic pioneer (organic production excludes genetic engineering as a key tenet): All cotton in Patagonia's own clothing line are organically sourced and the company is currently trying to enter the organic food market as a major player with its new Patagonia Provisions brand while playing a lead part in the establishment of a high-bar 'regenerative organic' standard that explicitly excludes next generation genetic engineering techniques.

Patagonia's former activist-style embrace of all things non-GMO and organic stands in stark contrast to its newer business decision to lend its name to the risky venture of synthetic biology textile production. This in turn sends a very confused signal to its consumers and industry partners about exactly what sort of agricultural system Patagonia believes in. Does it stand with sustainable natural fibre farmers or is now more enraptured by Silicon Valley technofixers? It's a contradiction that Patagonia seems to prefer not to address. In early 2018, even while CEO Rose Marcario told organic executives in a key speech in Los Angeles that her company cares about "issues of food sovereignty", corporate concentration and "fairness for farmers,"[57] Patagonia executives at the same meeting privately told civil society that Patagonia was comfortable to continue its partnership with syn bio start-up Bolt Threads - a company whose business model is exactly to displace farmer-based production of natural fibres with proprietary biotech proteins.[58]

Patagonia's response to food and farm activists who have shared their concerns with the company is that it has not yet made a firm decision on whether to use Bolt Thread's fibres in its commercially available clothing and that the company's interest is currently purely on the technical level - evaluating the claims for strength and elasticity that Bolt are making for their fibres.[59] Patagonia, however, admits to working in close collaboration with Bolt Threads to help improve their fibres towards potential commercial use and won't rule out selling genetically engineered clothes in the near future. More significantly, Bolt Threads as a company has in turn continuously used the fact of this collaboration with Patagonia in its publicity to investors and to the media to bolster its own appearance of commercial success while borrowing the environmental sheen of Patagonia to greenwash its product. Most media reports of Bolt Thread's production of 'spider silk' lean heavily on this perceived endorsement by Patagonia (as well as designer Stella McCartney) as a key source of eco-credibility for this genetic engineering firm.[60] Patagonia has seemingly not asked its biotech partner to stop namedropping.

For the sake of full transparency, if Patagonia decides to u-turn on genetic engineering and back biotech textiles, they should at least come clean with consumers about their contradictions: Patagonia should as a minimum promise to unambiguously label as such any genetically engineered textiles that it sells and seriously re-evaluate its positioning as an organic and GMO-free pioneer brand.

A Patagonia anti-GMO ad.



Source: Shreya Sonar

Biosynthetic Silk and Microplastic Pollution: A False Solution

The fast fashion industry has recently been getting bad press for how synthetic textiles contribute to microplastic pollution in the oceans.[61] Plastic marine pollution – so vast that it can be seen from space – severely threatens aquatic habitats and marine organisms, with as-yet-uncalculated costs to human health. Microplastic pollution of marine and freshwater environments has been recognized as a planetary crisis for nearly two decades. Only recently has it become clear that tiny particles of synthetic fibres (plastic microfibres) shed from human-made, synthetic textiles (like polyester, nylon, acrylic, and spandex), are one of the major contributors to microplastic pollution: recent estimates suggest that as much as 20% to 35% of all primary source microplastics in the marine environment are fibres shed from synthetic clothing, particularly while washing, and the amount is increasing.[62] Biosynthetic fibres that mimic synthetic polyester, like DuPont's Sorona fibres, only deepen and extend these concerns – Sorona is neither biodegradable nor compostable. Because biosynthetic silk appears to mimic natural fibres that do have biodegradable properties (such as natural spider silks), there have been suggestions that bioengineered silk could be part of the fashion industry's response to this mounting crisis.[63] Some high-profile supporters of spider silk, such as fashion designer Stella McCartney, are also outspoken on the topic of addressing ocean microplastic pollution.[64]

However, the long-term degradability of bioengineered silk threads cannot simply be assumed or extrapolated from natural spider silk. The proteins being developed by biotechnology companies are novel and distinct from natural spider silk and should be independently assessed for degradation claims and impacts once released into water and soil.

More significantly, there is no clear economic link between putting a biosynthetic silk on the market and reducing the burden of synthetic fibres entering the world's oceans. Bolt Threads, for example, has acknowledged that its threads primarily compete with natural silk (which is already biodegradable) and will "never compete with polyester just on cost," but hopes to one day engineer specialty stretchy textiles that are biodegradable for small niche markets such as yoga clothes or lightweight jackets.[65] This may be a good strategy to capture profits from well-heeled eco-conscious consumers, but it does not appear to be an effective strategy for addressing the flood of cheap fast fashion clothing responsible for ocean plastic pollution.[66]

Spinning Failure as Success: Synthetic Biology's Commercial Track Record

Biosynthetic pathway engineering is highly complex, expensive and far from routine. Although syn bio companies point to commercial success in the scale-up of high-value, low-volume products (such as flavours, fragrances and small-batch specialty chemicals), the biosynthesis platform has a mixed record when it comes to industrial scale-up of large volume products.

- **Biofuels:** One decade ago, synthetic biology start-ups and petrochemical industry partners were making grandiose claims about using designer microbes to produce plentiful, sustainable, low-cost biofuels in giant fermentation tanks. Synthetic biology entrepreneur Craig Venter boasted of synthetic biology's "tremendous potential, possibly within a decade, to replace the petrochemical industry."[67] Despite the hype, efforts to biosynthesize cheap substitutes for petrochemicals went bust because companies couldn't achieve commercial scale-up at competitive prices.
- **Anti-Malarial Drug:** Similarly, millions of dollars in R&D were invested in high-profile attempts to biosynthesize artemisinin – a key ingredient in the world's most effective anti-malarial drugs. (The anti-malarial compound is traditionally sourced from an estimated 100,000 small farmers in Asia and Africa who grow *Artemisia annua* – the sweet wormwood crop). Synthetic biology enthusiasts boasted that syn bio's platform would make the anti-malarial drug cheap and plentiful: "If we scale this up, in six months we will be at a point where 400 reactors (that run continuously) will be sufficient to produce the entire world's supply. Our reactors (…) could shave the total cost of the drug by a third."[68] Attempts to scale-up and commercialize synthetic biology's highly-celebrated anti-malarial compound were vastly over-hyped and short-lived. The pharmaceutical factory that briefly produced the biosynthesized anti-malarial compound was unceremoniously sold in 2016.[69]
- **Flavours & Fragrances:** Synthetic biology companies have proven able to manufacture high-value, low-volume flavour and fragrance compounds in engineered microbes. Evolva's vanillin flavour and Isobionics/DSM's orange fragrance are already commercially available- and many more flavour and fragrance compounds are in the pipeline.[70] Existing regulations in the EU and US may allow these products (derived from fermentation and other microbiological processes) to be labelled as "natural" ingredients/products, positioning them to compete with botanically-derived compounds as well as with their synthetic (chemically-derived) counterparts. Under current labelling regulations in the EU and US, consumers of natural flavours and fragrances have no way of knowing if the natural ingredient they seek is derived from botanicals or biosynthetic organisms.

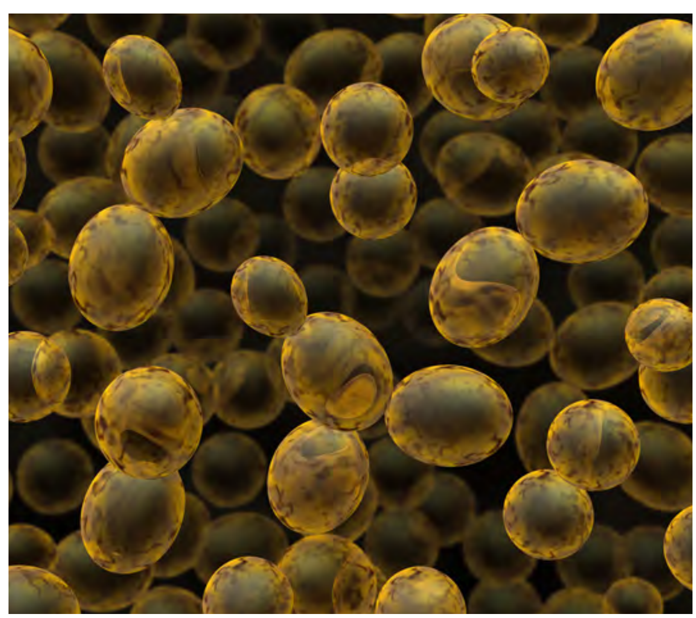
Past and Present Efforts to Genetically Engineer Fibres: Three Not-So-Easy Pieces

The genetic engineering of fibres is nothing new. Over the past two decades, bioengineers have introduced at least three approaches to genetically engineer fibres:

1. **GE Cotton:** Thanks to Monsanto and a handful of agrochemical giants, genetically engineered (GE) cotton was planted on an estimated 22 million hectares worldwide in 2016.[71] Despite its commercial success, GE cotton hasn't helped small farmers[72] or benefited consumers – but it has generated blockbuster sales for Monsanto's flagship chemical weed killer, glyphosate (tradename RoundUp). Since 1996, GE cotton has been engineered for two genetic traits: 1) to tolerate heavy doses of chemical herbicides, especially glyphosate; 2) to resist some insect pests with built-in insecticidal toxins.[73] Over time, both insects and weeds are increasingly evolving resistance to both GE cotton traits, leading to documented GE cotton crop failures in the field.[74] In August 2018, Australian media reported that a team of synthetic biologists from government science programme CSIRO were working on developing a bioengineered cotton with altered cell wall structure to mimic many of the properties of synthetics, such as being stretchy, non-creasing and even waterproof, while retaining its natural fibre feel. "We've got a whole bunch of different cotton plants growing; some with really long thin fibres, others like the one we call 'Shaun the Sheep,' with short, woolly fibres," explained CSIRO scientist Dr Madeline Mitchell.[75]

2. **GE Animals:** Other synthetic biologists are focusing on the genetic engineering of animals (goats and silk worms) to produce novel fibres that these animals could never produce in nature. Beginning in the late 1990s, Montreal-based Nexia Biotechnologies introduced silk-spinning genes from spiders into goats, with the goal of harvesting a super-strong silk protein from goat's milk.[76] Nexia is long gone, but the "spider goats" eventually made their way to Utah State University where researchers continue to develop new generations of transgenic goats endowed with silk-making genes from golden orb spiders.[77] A start-up in The Netherlands, Inspidere, has worked with the synthetic spider silk from the Nexia engineered goats to develop a proof of concept 'bulletproof' skin that mixes spider silk and human skin cells[78] and offers synthetic spider silk on its website.[79] Other companies seek to modify the silkworm's natural ability to spin silk fibres. Kraig Biocraft Laboratories, Inc. has inserted its patented spider silk gene sequences into silkworms. The company's GE silkworms are now spinning proteins composed of a mixture of both spider and silkworm silk.[80] In Japan, Immuno-Biological Laboratories Company has successfully created a GE silkworm that produces 6-7 mg of human collagen from a single cocoon. The collagen harvested from modified silkworms is already being used in commercial cosmetic products.[81]

3. **Synthetic GE Microbes:** As discussed in this report, synthetic biologists are now using synthetic DNA to build microorganisms (i.e., yeast and bacteria) that are engineered to secrete fibrous materials in industrial fermentation tanks. See Table 1: Companies Using Microbe-Based Biosynthesis for Fibre Manufacturing Targeting the Apparel Sector.



Beyond Syn Bio Silk

Although recent media attention highlights efforts to develop genetically engineered silk-like fibres, technology start-ups also aim to use synthetic biology's designer organisms to develop other bio-inspired products for the fibre/fashion/materials industry. These include, for example:

- **Biofabricated Leather Analogs:** Modern Meadow, a Brooklyn-based biotech start-up, is growing proprietary strains of genetically engineered yeast that secrete leather-like proteins in fermentation tanks. The company claims its lab-grown proteins are identical to bovine collagen – a fibrous protein that forms connective tissue and gives animal skin its strength and elasticity. The company's collagen fibres can be assembled into layers, resembling sheets of raw leather that can then be tanned, dyed and finished like animal-derived leather – without the animals. By tweaking its genetically modified yeast products, the company aims to optimize collagen fibres with made-to-order functional properties (i.e., texture, weight, appearance).[82]

"It's biology meets engineering. We diverge from what nature does, and we can design it and engineer it to be anything we want."[83]

—Andras Forgacs, CEO of Modern Meadow

- **Lab-grown Horns and Tusks:** US-based syn bio start-ups Pembient and Ceratotech are biofabricating keratin – fibrous proteins that are a major component of skin, hair, wool, nails, hooves, horns and teeth. Their goal is to produce lab-grown rhino horn substitutes that they believe will reduce the incentive to poach endangered wildlife. Pembient initially used engineered yeast cells to produce keratin and used a 3D printer to mold a prototype horn.[84] Pembient and Ceratotech are now using tissue-engineering to coax stem cells from a rhino or other animal to grow into the cells that produce keratin.[85] A team of University of Oxford (UK) researchers is attempting to biosynthesize the ivory that makes up elephant tusks, a task that is especially complex because ivory consists of two materials, collagen and hydroxyapatite (a calcium-based mineral).[86]
- **Syn Bio Dyes:** UK-based start-up Colorifix is using genetically altered bacteria to make pigments for fabrics. The company claims that its engineered microbes not only produce pigments, but also the company's process "fixes" the pigments onto fabric.[87] Colorifix asserts that, if scale-up is successful, biosynthesized pigments will save water, reduce waste and eliminate the need for harmful chemicals (solvents, acids and heavy metals) that are typically used in the textile dying industry. Additionally, leading synthetic biology company Ginkgo Bioworks has been experimenting with biosynthesized dyes for fabrics. They have been working with bio-design artist Natsai Audrey Chieza who has engineered the soil bacteria *streptomyces coelicolor* to express blue, pink and purple dyes.[88] Chieza, who is establishing her own company, Faber Futures, says she is currently working with two brands (one luxury boutique brand and a sports apparel brand) to test the commercial impact of producing her syn bio dyes at scale.[89]
- **Engineered Living Materials:** A New York-based company, Ecovative, was founded on the premise that mycelium (the root system of a mushroom) is "nature's glue" – and can be used to bind agricultural waste and wood together to make furniture and household products. In April 2018, Ecovative announced a partnership with Bolt Threads to produce a high-end mycelium handbag that it will launch under the Stella McCartney brand.[90] Last year, Ecovative won a $9 million R&D contract from the US Defense Advanced Research Projects Agency (DARPA) to develop next generation building materials "with attributes of living systems." Ecovative is collaborating with syn bio researchers to grow a living hybrid composite building material, that can be genetically programmed to have "responsive functionality" (e.g., wound repair, protective surfaces, and/or infection response).[91]

MIT's "moisture responsive workout suit" is lined with microbial cells that shrink and expand to create vents in response to the athlete's body heat. Photo: Hannah Cohen/MIT News Office

High-Tech Threads on Steroids

The application of new technologies to fibres and fabrics extends far beyond bioengineered fibres. In the long term, high-tech fashion firms may integrate a suite of new technologies to transform traditional fibres, textiles and materials – including electronics, synthetic biology, nanotechnology and more. Inspired by last century's advances in the semiconductor chip manufacturing industry, techno-optimists envision the convergence of semiconductor technology into fibre and textile manufacturing – the so-called "Moore's Law for Fibers."[92]

> **"We are just at the beginning, only starting to imagine what a fabric could do if it's packed with all the stuff of technology."**
>
> **—MIT material scientist, Alexander Stolyarov**[93]

In 2016, the Massachusetts Institute of Technology (MIT) launched its Advanced Functional Fabrics Institute (AFFI) with $320 million in start-up funds from industry and the US Department of Defense. The AFFI network includes academic, industry and government researchers who are dedicated to transforming "traditional fibers, yarns, and textiles into highly sophisticated integrated and networked devices and systems."[94] By embedding semiconductors and sensors into textiles, AFFI researchers seek to accelerate commercialization of "fabrics that see, hear, sense, communicate, store and convert energy, regulate temperature, monitor health and change color."[95]

AFFI research is not limited to multifunctional fibres/fabrics. The research network is "poised to deliver revolutionary advances across the entire fabric supply chain" including weaving and knitting capabilities and end-product fabrication.[96] The "smart" fabric and apparel products include the following prototypes, for example:

- **Biohybrid Wearables:** A team of eighteen MIT researchers has designed prototypes of "biohybrid wearables" – a breathable exercise suit and a fluorescent running shoe with ventilating bio-flaps that open and close in response to human body heat and sweat.[97] The small flaps are lined with genetically modified bacterial cells that shrink and expand in response to changes in humidity.[98] The team's prototype running shoes feature moisture-sensitive cells that light up in response to humid conditions. According to the lead scientist, Wen Wang, "We use fluorescence as an example (...) In the future we can combine odor-releasing functionalities through genetic engineering. So maybe after going to the gym, the shirt can release a nice-smelling odor."[99]
- **Climate-Control Apparel:** In 2017, a team of fourteen Stanford University material scientists and engineers unveiled a new "smart" fabric that keeps you warmer or cooler depending on how it's worn.[100] The researchers engineered a piece of plastic polyethylene material with nano-sized pores that has two layers of coatings embedded within it. One coating is nanoscale carbon, a chemical that emits thermal energy. The other coating is copper,

a metal that traps heat. The wearer can adjust body temperature – warmer or cooler – by turning the material inside out.[101]

» **Military Threads:** The MIT-based "Defense Fabric Discovery Center" (DFDC)[102] opened its doors in 2017 with the mission to "develop advanced fiber and fabric technology to protect the US military and address national security problems."[103] DFDC is developing prototype fabrics that will integrate advanced sensing, energy, and communication microelectronics into the fabric of soldiers' uniforms and gear. Possible applications include multi-material fibres and textiles that can be used to thwart improvised explosive devices (IEDs), camouflage vehicles, generate energy to charge batteries, and monitor soldiers' vital signs.

» **Commercial Fibre Hacking:** Beyond futuristic prototypes, Ministry of Supply, a Boston-based high-tech fashion start-up, is selling its "science-based clothing line." In the words of company co-founder, Gihan Amarasiriwardena, "Instead of hacking code, we're hacking fibers."[104] The company's products include "aerospace-tech dress shirts"[105] and socks that use coffee grounds (molecularly bonded to the yarn's surface) to mitigate odour. In 2017, the company unveiled the fashion industry's first 3D-knitting machine to make personalized blazers on demand.[106] According to the company's website, "Warp-knitting unlocks structural stretch that doesn't rely on materials that break down over time." That's because the company uses spun petroleum-based polyester (i.e., synthetic plastic fibres).

The bottom line: Despite the technological wizardry, the enormous investment in R&D and the brain power of some of the world's most highly-trained scientists, our ecosystems simply can't endure more plastic-based fibres and fabrics embedded with chemical coatings to keep our bodies warm or cold. Far from the promise of sustainability, the development of "smart" clothes with built-in data storage or communication capability raises the appalling spectre of amplifying electronic waste and microfibre plastic pollution in one integrated package. The technologies also raise a fundamental question of "for whom?": Do athletes need "sweat responsive" workout clothes lined with microbial sensors or living cells that glow-in-the-dark? Novel 3D printers and knitting machines aren't spitting out fibres that are more sustainable or enhancing the livelihoods of workers.

Flax for linen flowering in the field.
Source: PaigeGreenPhotography

Synthetic Biology's Potential Environmental and Human Health Impacts

The environmental and human health impacts associated with synthetic biology are currently poorly understood. There is broad agreement that existing regulatory systems and risk assessment protocols may be inadequate to address the potential risks of new products derived from synthetic biology, and the UN Convention on Biological Diversity is exploring the development of new international guidelines for risk assessment of synthetic biology.

In the US context, a review conducted by the Synthetic Biology Project of the Woodrow Wilson International Center concluded that the existing US regulatory system is "ill-suited to address all the regulatory implications of new products derived from synthetic biology."[107] A fundamental challenge in assessing the safety (especially environmental safety) of the production of new bioengineered fibres is that genetically engineering organisms (including production strains) may lead to unexpected changes including the potential production of additional toxins and contaminants. For example, engineered microorganisms for fibre production may continue to be active after they are disposed of, and in a worst-case scenario, they may continue to secrete fibre proteins into soils, waterways or, if ingested or taken onto the skin, into or onto living beings.

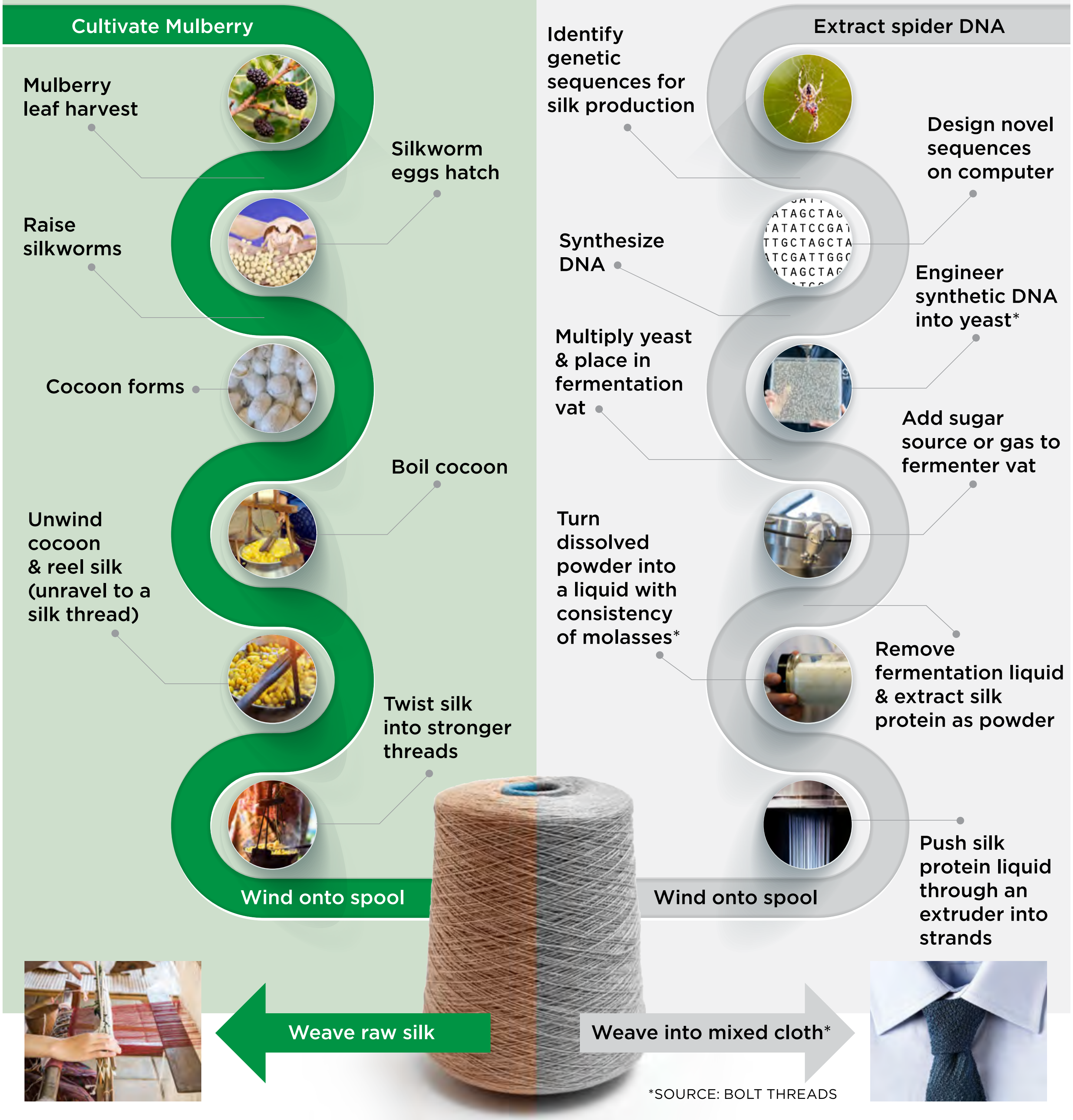
COMPARING NATURAL AND SYNTHETIC SILK PRODUCTION

NATURAL

Millions of farmers earn livelihoods from producing silk. In China, sericulture dates back 5,000 years.

SYNTHETIC

Synthetic biology companies use genetically-modified organisms to produce proteins similar to silk produced by spiders.



*SOURCE: BOLT THREADS

Biotech-waste: A New Stream of Industrial Pollutants?

Just as the burgeoning electronics industry created the unforeseen challenge of toxic e-waste (electronic waste), the rapid growth of industrial-scale biosynthesis could deliver a new stream of *b-waste*[108] (biotech waste).

A 2017 study by the US Army Corps of Engineers and University of Arizona scientists concludes that existing approaches of "life cycle assessment" – the standard method used to assess and manage risks associated with industrial chemical pollution – simply cannot be applied to applications of synthetic biology.[109]

> **"With a limited understanding of the potential ecological impacts, regulators and key stakeholders in industry are challenged to identify best practices and safety requirements for various applications of synthetic biology research such as with the containment and safe disposal of engineered organisms without allowing such artificial information to proliferate in the natural environment."[110]**
>
> **—Seager et al, "Why Life Cycle Assessment Does Not Work for Synthetic Biology," 2017**

Containment of organisms developed with synthetic biology is not practical or possible. Experts conclude that physical containment of synthetic organisms is not practical, especially within large-scale production systems.[111] A US Presidential Commission acknowledged in 2010 that "contamination by accidental or intentional release of organisms developed with synthetic biology is among the principal anticipated risks."[112]

Bioengineered yeast designed to secrete novel silk proteins will be produced in contained systems – industrial fermentation tanks – also known as biorefineries. Manufacturing facilities that use synthetic microbes in contained systems such as biorefineries (e.g., for fermenting biofuels and/or bio-based chemicals), are not expected to maintain the same level of containment as biosafety labs. Conventional biorefineries, analogous to breweries, routinely experience escapes of cultured yeast (via air, water, waste streams, workers, and other pathways of exposure).[113] How will biosynthesis fermentation waste be managed? What impact will unintentional or accidental release of synthetic organisms have on ecosystems and biodiversity?

In the case of a synthetic yeast designed to secrete engineered silk proteins in industrial-scale fermentation tanks, the fate and potentially disruptive impacts of novel organisms on soil ecology and the soil microbiome[114] is unknown. Yeasts in particular move easily through soil and air and exchange genetic material promiscuously. While engineered organisms may not have a fitness advantage in the open environment, it is also possible that they could find an ecological niche, survive and reproduce, and lead to undesired cross breeding with other organisms.[115]

Although synthetic biology facilities may voluntarily take greater precautions to contain engineered microbes,[116] "the behavior of synthetic biological systems remains unpredictable."[117] Unintentional releases (including from accidents and human error) are inevitable. In 2013, the US company Amyris reported one such accident involving transgenic yeast at one of its bio-fermentation facilities in Brazil.[118] About 20 litres of a solution containing transgenic yeast leaked into the environment. The biosynthesized yeast, approved for "confined" use, was designed to produce diesel from sugar cane. According to the company, appropriate measures were taken to contain the spill, but since they are not regulated in most countries there is no way of knowing how many spills – intentional or accidental – go unreported in a growing number of biosynthesis fermentation sites worldwide.

Worker Safety/Occupational Hazards

With the rapid growth of industrial-scale bioengineering, there is also concern about potential worker safety and occupational hazards related to synthetic biology.[119] A 2016 article on synthetic biology and occupational risk observes: "There is a need to review and enhance current protection measures in the field of synthetic biology, whether in experimental laboratories where new advances are being researched, in health care settings where treatments using viral vectors as gene delivery systems are increasingly being used, or in the industrial bioeconomy."[120]

Synthetic Biology's Potential Threat to Natural Fibre Producers

If bioengineers can engineer microbes to mimic silk or the properties of other natural fibres on a commercial scale at a competitive price, it could disrupt natural fibre markets and up-end the livelihoods of millions of people.

An estimated 58 million households (about 225 million people) are employed in natural fibres production, primarily in the Global South. In 2016, the farm value of natural fibre production was around US$50 billion.[121]

What are Natural Fibres?

"Natural fibres" are materials produced by plants and animals that can be spun into filaments or thread – the building blocks for textiles, the fashion industry, and countless fibre materials. Millions of smallholder farmers and resource-poor families depend on the production of natural fibres for their livelihoods, especially in the Global South. Fibres of plant and animal origin not only contribute to food security, livelihoods and poverty alleviation, they are sustainable, biodegradable resources. Natural fibres are land-based agricultural commodities and most have been produced by farming communities for millennia. The carbon footprint of natural fibres is not easily calculated because of the diversity of materials, production methods and the gaps in life-cycle assessment data.[122] In comparison to petrochemical-derived synthetic fibres, however, natural fibres are "climate friendly" with significantly lower greenhouse gas emissions.[123] At the end of their life cycle, natural fibres are 100% biodegradable. In recognition of the vital roles played by natural fibres, the United Nations Food & Agriculture Organization declared 2009 the "International Year of Natural Fibres."[124]

Plant-based natural fibres include: Abaca, coir, cotton, flax, hemp, jute, ramie, sisal.[125]

Animal-based natural fibres include: Alpaca, angora, camel, cashmere, mohair, silk, wool.[126]

Despite their environmental and income-generating benefits, the global market for natural fibres has been shrinking due to competition from synthetic fibres. Small-scale farmers and resource-poor communities are being driven out of international textile markets because natural fibres can't compete with record-breaking production of cheaper, human-made synthetic fibres.

It's difficult to estimate the number of people employed in natural fibre production because many countries have spotty data collection; most producers are small farmers (mostly family or household-based production); many producers do not produce fibre as a primary crop; and hired labour is often informal, seasonal and part-time. According to industry analyst Terry Townsend, "a reasonable estimate of total employment in natural fibre industries, including family labour, hired labour and employment in industries providing services to agriculture, and including both full time year-round employment and part time or seasonal employment, is around 58 million households (about 225 million people), or about 3% of the world's population."[127]

Natural fibre producers have been facing an avalanche of competition from cheaper, synthetic fibres – that is, human-made fibres like rayon, nylon, polyester and polypropylene. Natural fibres' share of total fibre consumption has been shrinking steadily for the past half century. In 1960, natural fibres accounted for 78% of total fibre production, plunging to a 40% share by 2008. Today, natural fibres account for just 30% of the worldwide fibre market.[128]

Cotton – the king of natural fibres – accounts for over three-quarters of total natural fibre production, and 69% of the estimated farm value. (Cotton accounts for one-quarter of the worldwide fibre market – including both natural and synthetic fibres). Wool accounts for approximately 1%. Other natural fibres (including silk, Abaca, Bastfibers,[129] Flax, Hemp, Kapok, Ramie, Sisal, Henequen and similar hard fibres) collectively account for less than 5% of total natural fibre production.

The textile industry often points to the limitations of land- and water-intensive natural fibres. Reminiscent of Big Ag's defence of Big Food as the only sure way to feed a hungry world, the textile industry observes that the "growing global population is increasing competition for productive land and freshwater resources."[130] A 2017 report observes: "The increasing demand for land for food production could significantly limit any possible expansion of land-intensive cotton- or wool-related agriculture in the future and so restrict the output of these fibres."[131]

Natural fibres are clearly not a one-size-fits-all panacea for all the world's textile needs, and the status quo is unacceptable, especially when it comes to chemical-intensive and water intensive production of conventional cotton. It is important to recognize the far-reaching economic, cultural and biodiversity contributions of natural fibres to rural and farm-based economies, and to acknowledge that sustainable and diverse farm systems can and are being used to grow natural fibres. Women play dominant roles in harvesting, processing and weaving many traditional natural fibers such as abaca and the lesser known banana pineapple and lotus root fibers that are grown as secondary crops in family holdings to provide additional income for many households in the Global South.

World Natural Fibre Production, 2016

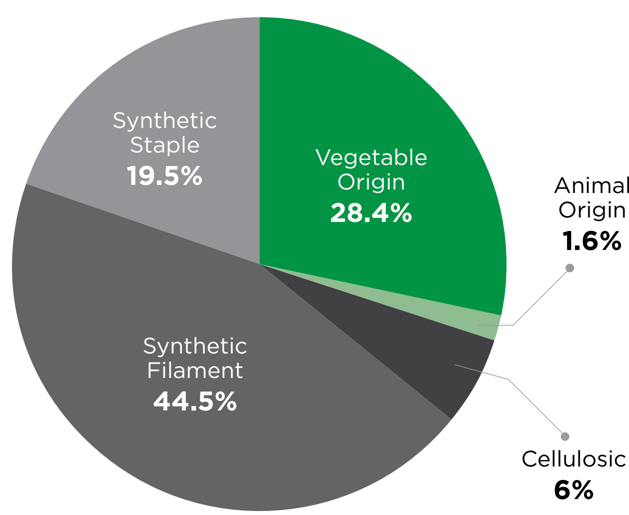
Fibre	Metric tons	% of total natural fibre market	Farm Value ($ billion) estimate	Households employed (millions) estimate
Cotton	23,000,000	77%	$34.7	45
Jute	3,300,000	11%	$2.2	6
Other*	1,440,000	4.8%	$3.4	1
Coir	1,157,000	3.8%	$0.7	1
Wool	1,100,000	3.6%	$9.0	5
TOTAL	**30,000,000**	**100%**	**$50 billion**	**58 million**

Source: Terry Townsend, Cotton Analytics[132]

** includes Silk, Abaca, Bastfibres, Fibre crops not specified elsewhere, Flax, Hemp, Kapok, Ramie, Sisal, Henequen and similar hard fibres.*

World Fibre Production, 2016 (estimate)

Type of Fibre	Metric tons	% of total worldwide fibre production
Natural Fibres		
Vegetable Origin	28,700,000	28.4%
Animal Origin	1,300,000	1.6%
Total Natural Fibres	30,000,000	30%
Synthetic Fibres		
Cellulosic	6,200,000	6.0%
Synthetic Filament	45,000,000	44.5%
Synthetic Staple	19,800,000	19.5%
Total Synthetic Fibres	71,000,000	70%
TOTAL World Fibre	101,000,000	100%



Source: Terry Townsend, Cotton Analytics[133]

Silk production at silk Island or Koh Dach near city of Phnom Penh of Cambodia

Case Study: The Potential Impacts of Syn Bio Silk on Natural Silk Producers

Traditional Silk Production

In China, the ancient practice of cultivating silkworms to produce silk (known as sericulture) dates back 5,000 years. Today, silk is produced in over 60 countries, but China and India are the largest producers by far – accounting for over 97% of total silk production. Natural silk is also produced in Uzbekistan, Thailand, Brazil, Vietnam and Madagascar, among others.

Employment in the Natural Silk Sector

Natural silk occupies a tiny sliver of the global textile market, but the labour-intensive silk industry generates millions of jobs for farm families, reelers, loom operators and weavers – especially in Asia. Millions of farm families earn their livelihoods from silk. In 2016, the farm value of silk production was about US $800 million.[134] In 2016, raw silk production (silk filament) reached 193,000 metric tonnes.[135]

Dubbed the "queen of fabrics" because it was once reserved for royalty, silk is still a luxury fabric prized for its exquisite sheen, softness, exceptional strength, high absorbency and light weight. Silkworm farming is extremely labour intensive. The average price of 1 kg of raw silk is typically about 20 times the unit cost of cotton.

In 2016, the estimated value of the global silk market was US $11.7 billion[136] (that is, the value of finished silk products used in textiles and apparel).

Could Biosynthetic Silk Displace Natural Silk?

It is unclear at this time if synthetic biology-based production of silk proteins could ever compete with natural silk in either price or volume. In August 2018, Forbes reported that Bolt Threads' engineered silk costs more than $100 per kilo, making it pricier than high-quality natural silk from silkworms, which goes for between $60 and $100 per kilo. But the same report explained that the company believes it can get the cost down to a comparable level at commercial scale—and that eventually it can push it below

$40 per kilo, indicating that Bolt Threads sees competing against traditional silk markets as a part of its future profits.[137] One of Bolt Thread's lead investors (Formation 8's Jim Kim) expressed to the investment press that he saw their product as an alternative to traditional silk manufacturing: *"[...] the processes that Bolt Threads has come up with are far easier than natural silk manufacturing, which traditionally requires silkworms and plenty of mulberry leaves, which are plants threatened by climate change and the silk industry."*[138]

Indeed, on its website Bolt Threads explicitly touts its product as a competitor to natural silk: "Our fabrics will combine the best qualities of silk but will look and feel quite different from traditional silk, and also be easier to wash and wear."[139]

Biodiversity Benefits of Mulberry Farming Systems

The majority of commercially-produced silk is produced by silkworms (*Bombyx mori)* that feed exclusively on the leaves of mulberry, a perennial tree/bush crop (genus *Morus*).[140] The leaves of the mulberry can be harvested five times per year, and some varieties yield for 25-30 years. Over millennia, farmers have selected and improved thousands of varieties of mulberries that are used to feed silkworms. More than a thousand varieties of mulberry are found in China alone.

- In China, some 626,000 ha of mulberry bushes/trees are cultivated to feed silkworms.[141]
- In India, the area devoted to mulberry cultivation is around 282,000 ha.[142]
- In Thailand, almost 17,000 ha were devoted to mulberry in 2013.[143]

Mulberry offers a range of biodiversity benefits beyond silkworm production.[144] Mulberries are harvested as a feed and forage for livestock, and as a traditional dye for fabric. The young leaves and stems of mulberry plants are eaten as a vegetable. Traditional Chinese medicine uses mulberry fruit to treat constipation and diabetes, among other conditions. The bark is used to treat fever, headaches and more. Mulberry fruit is also gaining popularity as a 'superfood' for its high content of antioxidants, vitamin C and other nutrients.

As traditionally practiced in China, mulberry is integral to diverse, ecologically-based farming systems: "Integration of fish, livestock, and crop production in China has been refined for over 2,000 years. The system recycles resources, reduces organic pollution (livestock and poultry manure are good organic fertilizers for fish farming), and combines fish farming with mulberry cultivation for raising silkworms."[145]

How do Silkworms Make Silk?

The labour-intensive process of cultivating silkworms begins with the eggs of the silk moth, which hatch to form larvae, known as silkworms, *Bombyx mori*. About 90% of all silkworms feed exclusively on the leaves of the mulberry tree. The silkworm secretes a fluid protein from its glands that hardens into a fibre.[146] The worm uses this protein fibre (a continuous silk filament) to spin its cocoon. After the cocoons are harvested, hot water is used to soften the hardened fibre, allowing the silk filaments to be unwound (the larva of the silkworm is killed in the heating process). The unwinding of silk filament from cocoons is called "reeling." Each silk filament spans 500 to 1,500 meters in length, and 10-13 microns in diameter; single filaments are combined to make silk thread.[147] One cocoon can yield approximately 900 meters of silk filament.[148]

Leading Silk Producers, 2016

Country	Production (Million Tons)	% of world total
China	158,000	82
India	30,000	15.5
Uzbekistan	1,300	0.7
Thailand	712	0.4
Brazil	650	0.3
Vietnam	500	0.25
Madagascar	6	.003
WORLD TOTAL	193,000	99

Source: International Sericultural Commission[149]

Although some segments of silk production (in China, for example) are highly automated, most of the silk industry still operates on the scale of a cottage-based industry.[150] Women typically provide 60% of the labour in silk production.

According to the International Sericulture Commission:

» China's silk sector employs an estimated 1 million workers.[151]

» India, the world's second largest silk producer, employs more than 7.6 million people across 51,000 villages – including farm production, hand looms, power looms and weavers.[152]

» In Thailand, over 100,000 farmers and 20,000 weaving families are involved in silk production; the majority are small-scale farmers who work part-time to supplement farm income.[153]

History Lesson: **Industry Greenwashing and the Case of Rayon/Viscose and Cellulose-Based Fibres**

Although viscose/rayon is often marketed as a "green" material because it is derived from cellulose, the toxic chemical process that is widely used to manufacture it makes a mockery of industry's claim that rayon is a "green" or "sustainable fibre."[154] Known as the first human-made fibre, rayon/viscose has been manufactured on an industrial scale since the end of the 19th century. Rayon fabric, prized for its softness and drape, was often marketed as "artificial silk." Today rayon/viscose is considered a "semi-synthetic" fibre because it is made of cellulose (primarily wood pulp from trees) and therefore of natural origin.

For most of the 20th century, however, rayon manufacturing has been associated with chemical intensive, highly polluting methods that are used to process cellulosic fibres. For example, the chemical solvent typically used to produce rayon, carbon disulphide, used to extract and treat cellulose, is highly toxic, and has been linked to severe impacts on human health and the environment. Although rayon/viscose can be produced using methods that limit the release and exposure to harmful chemicals, it is not the industry standard. A 2017 report by the Changing Market Foundation reveals that many of the world's largest manufacturers of rayon/viscose, especially in Asia, are using chemical-intensive and highly polluting methods to process cellulosic fibres.[155] In addition, in some cases the wood used to manufacture cellulosic fibres has been sourced illegally, including from ancient rainforests.

*Source: Flickr, Kotomi_*

Conclusion

Synthetic biology's high-tech fibre future is being sold as "green" and "eco-friendly," but it threatens to undermine the livelihoods of millions of natural fibre producers and unleash new environmental hazards such as b-waste proliferation while not addressing significant threats such as ocean microplastic pollution.

Synthetic biology's genetically engineered fibres won't put the brakes on the textile industry's fast fashion. Rather, these technologies target a high-end and specialized market that constitutes a tiny part of the apparel market yet will have far-reaching impacts on the environment and livelihoods that depend on natural fibres. Far from the promise of sustainability, the current development of "smart" techno-fibres could add to and amplify new sources of industrial pollution.

Dressed for Success?

Current "success" stories do not inspire confidence:

- DuPont's Sorona, the first commercially successful biosynthesized product used to make apparel fibres was lauded as a green, eco-friendly alternative to fossil fuel-based synthetic fibres. In fact, Sorona is mostly derived from petroleum and is neither biodegradable nor compostable, so its fibres become ocean microplastic alongside synthetics. It also relies on a chemical-intensive monoculture crop – genetically engineered corn – as a feedstock.
- Bolt Threads is aiming to compete against a genuinely natural fibre by name-dropping its high profile eco-minded partners (Stella McCartney and Patagonia) and hyping its supposedly stronger-than-steel-spider-silk, even while acknowledging that its current biosynthesized silk is not particularly durable, stretchy or even waterproof.[156]

The environmental and human health impacts associated with synthetic biology are currently unknown, and the behaviour of synthetic biological systems is unpredictable. There is broad agreement that existing regulatory systems and risk assessment protocols – in the US and internationally – are inadequate to address the potential risks of new products derived from synthetic biology.

Although syn bio companies are now focusing on high-value fibres such as silk, they claim that microbes can be engineered to produce synthetic proteins that mimic the performance qualities and properties of virtually any fibre or material – natural or synthetic. In the future, high-tech fabrics may converge with nanotechnology, 3D printing and electronics to create fabrics that are essentially wearable technology.[157]

If bioengineers successfully engineer synthetic microbes to mimic silk or the properties of other natural fibres on a commercial scale at a competitive price, it could disrupt natural fibre markets and up-end the livelihoods of millions of people. Millions of smallholder farmers and resource-poor families (an estimated 58 million households) depend on the production of natural fibres for their livelihoods, especially in the Global South. Fibres of plant and animal origin not only contribute to food security, livelihoods and poverty alleviation, they are sustainable, biodegradable resources.

Sustainable fibres have been around for centuries: plant and animal-based natural fibres are 100% biodegradable, renewable and they support the livelihoods of millions of small-scale farmers and rural communities worldwide. Natural fibres, and the farm families who produce them, are the single most important resources for building a truly sustainable fibre economy.

Recommendations

Our future depends on a radical transformation of the industrial textile economy. But new fibre technologies based on synthetic living organisms are not the solution.

Technology Assessment: Existing regulatory systems and risk assessment protocols, including life cycle assessment, in the US and internationally, are inadequate to address the potential risks of new products derived from synthetic biology. Evaluation of novel fibre technologies must go beyond a narrow technical risk/benefit analysis to include a broader, participatory technology assessment. It includes a system-wide lifecycle approach that considers all phases of fibre production, consumption and disposal including a full assessment of the social, environmental economic and ethical impacts of new fibre technologies.

Need for Transparency: Given the hype and glowing media coverage surrounding high-tech fibre fashion, it's difficult for consumers to unpack the industry's claims of "sustainability" and "natural." Apparel/fashion companies that use or support the development of bioengineered fibres and materials must be fully transparent, including about their partnerships and investments. Just as the 'right to know' and label genetically engineered ingredients in food is a cornerstone of consumer rights advocacy, companies that buy or sell biosynthesized fibres must provide information to consumers about all steps in the fabric supply chain that involve genetic engineering processes – including labels indicating GE fibre content directly on the clothing. Truth-in-labelling laws should prevent apparel companies from making false or misleading claims that equate biosynthesized fibres with "natural" or "sustainable."

Consumers actions: Oslo Consumption Research (Norway)[158] offer three common-sense strategies to put the brakes on fast fashion:

1. Reduce production and consumption of clothing.
2. Improve practices in the use phase of clothes (i.e., less frequent washing; extend life of garment).
3. Replace use of synthetic, plastic-based fibres with natural fibres where possible.

Supporting Soil to Soil Fibersheds: A growing movement of fibre producers, processors and workers are building and rebuilding regional and regenerative textile economies based on the creation of place-based textiles (known as fibersheds) that are designed to create lasting ecological and economic prosperity via the creation of cooperatively-based direct markets.[159] Fibershed systems foster economic development through livelihood creation, and by supporting and creating farming systems grounded in ecologically-enhancing forms of agriculture.

"I am doing no harm. I'm being quite useful. This thing is a Thneed. A Thneed's a Fine-Something-That-All-People-Need! It's a shirt. It's a sock. It's a glove, It's a hat. But it has other uses. Yes, far beyond that..." The Lorax said, *"Sir! You are crazy with greed. There is no one on earth who would buy that fool Thneed!" But the very next minute I proved he was wrong. For, just at that minute, a chap came along, and he thought the Thneed I had knitted was great. He happily bought it for three ninety-eight.* —Dr. Seuss, *The Lorax*, 1971

The hazards of industrial bio-based textile economies as explained by Dr Seuss: the entrepreneurial Once-ler ended up chopping down every last Truffula Tree – with tufts "much softer than silk" – to harvest and feed Thneed production and meet consumer demand, to a very bad end. While Thneeds sold for $398, Bolt Threads bioengineered 'silk' tie, sold at $317 dollars, is nonetheless slightly cheaper.

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