Greening Apparel Global Supply Chains

Green Fiber Technology Companies and Their Challenges With Commercializing New Technologies

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Lindsay Whitfield and Felix Maile

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ABSTRACT

The global apparel industry accounts for 8-10% of global emissions and therefore urgently needs to move away from fossil fuel-based energy sources, inputs and production methods. Achieving this requires replacing virgin polyester and cotton with novel green fibers that contain a significantly lower carbon content. Recent regulatory changes on circular economy principles in the EU and US have catalyzed the emergence of a range of new firms that seek to commercialize such novel green textile fibers. At the same time, we know less about the scale and speed with which these new fiber technologies are diffusing across the industry. To address this gap, the paper provides the first comprehensive mapping of firms that seek to commercialize green textile fibers, the technologies that are used, and the challenges that these firms face in entering apparel global supply chains. Our analysis draws on a range of sources including EU policy documents, apparel trade journals, firm websites and corporate reports, as well as interviews with green fiber technology firms, brands, and apparel manufacturers. We find that 129 firms are currently aiming at commercializing novel green fiber technologies, using biosynthetic and bio-assembly, regenerative cellulosic as well as chemical and thermal textile-to-textile recycling methods. Our in-depth analysis of the commercialization strategies of ten green fiber tech firms suggests that the challenges vary across technologies that are deployed. At the same time, there are a number of cross-cutting challenges that all innovating firms face, including obtaining finance for large scale production, as well as reaching price parity with conventional fibers.

1. INTRODUCTION

The textile and apparel industry accounts for 8-10% of all global CO_2 emissions. Textile and apparel production has occurred through globalized supply chains since the market liberalization in the mid-1990s. Large fashion brands and retailers coordinate geographically dispersed production in which apparel assembly, fabric production, yarn production, and fiber production are carried out predominantly in separate firms. These brands and retailers dominate the global supply chains because they control access to the major end markets in the US and Europe, capturing most of the profits. Notably, fossil fuel-based fibers drove growth in global apparel industry since the 2000s, as the price of polyester fibers was much lower than other fibers resulting in cheaper products but also creating high revenues for brands/retailers as well as commodity chemical producers. As a result, 38 percent of the total CO_2 emissions in the global apparel industry come from the production of polyester and conventional cotton fibers. There has been an increased usage of 'preferred fibers' such as certified cotton or viscose and recycled polyester from plastic bottles, but their impact on reducing emissions and pollution is limited.

Thus, 'greening' the global apparel industry requires commercializing what we call green fiber technologies, in which scientific and technical knowledge is applied to replace the use of fossil fuels as well as reduce the use of virgin resources. The green fiber technologies can broadly be divided into two categories: bio-based technologies and textile fiber to fiber recycling technologies. However, commercializing these green technologies is risky and costly because firms face a range of interlocking challenges that need to be addressed. This paper investigates dynamics around the commercialization of green fiber technologies in the global textile and apparel industry.

This paper provides the first mapping of developments around green fiber technologies. It answers the following questions:

- What are the new green fiber technologies, and who are the firms pioneering them?
- What is the role of government policy in incentivizing the commercialization of green fiber technologies?
- What challenges do firms seeking to commercialize these new technologies face?
- How are these challenges shaped by the existing industry configuration of the global textile and apparel industry in global supply chains with particular power dynamics among global brands/retailers, apparel assembly firms, textile manufacturers, and fiber producers?

Through the analysis of each of these questions, we aim overall to understand which factors explain why some firms are better positioned to successfully commercialize green fiber technologies than others, and thus also which technologies will come to set the industry standard and the pace at which it will happen.

Section two provides the theoretical perspectives and conceptual tools for thinking through these questions and shapes how we analyzed the data. Section three provides an overview of the current composition of global fiber markets, key policy shifts in the EU and to some extent the US, and the responses of apparel brands and retailers. The data comes from grey literature about the industry, quantitative databases, EU policy documents, apparel trade journal reports, an analysis of corporate reports for the top ten apparel brands/retailers, and some industry expert interviews.

Section four presents in detail the green fiber technologies, an overview of green fiber tech firms, and then ten case studies of green fiber tech firms covering different technologies. The mapping is based on a near comprehensive collection of data from online sources on all green fiber tech firms, which was carried out with research assistance from Chiara Laffi and Francesca Girelli. They collected data for over a hundred firms on the type of technology, when the firm was started and if it was a subsidiary or start-up, the current stage of production (lab, pilot or commercial), and sources of funding. Their research built on an earlier initial mapping started by Serine Linde Helland, using firms listed in a Textile Exchange study, as part of the CREATE project.[1] The ten firm case studies are based on an extensive review of online sources combined with interviews. The authors carried out interviews with five out of the ten case study firms as well as with other industry actors that had knowledge of the case study firms. The concluding analysis in section five draws on all of this material. A list of interviewees is contained in the appendix. We aim to continue with the interviews, so this paper is a first take on answering the questions based on the data collected so far.

2. CONCEPTUALIZING THE CHALLENGES TO COMMERCIALIZING GREEN FIBER TECHNOLOGIES

Why do some radical innovations get commercialized and others not, and what determines the pace? This question is answered in the innovation studies literature. Incumbent firms in the existing industry that have the organizational and financial capabilities to commercialize radical innovations often do not do so, while startups have more incentives to enter technologies in which they bypass the advantages of incumbent firms and build their own and take market share. However, startups often lack the necessary organizational and production capabilities, which they have to build, as well as the required financing, especially in light of weak or non-existent market demand. This section reviews the innovation studies literature on what drives the commercialization of new technologies and then considers how that applies in the case of 'green technologies' in which there is no fundamentally new product, such as microprocessor which drove computers, but rather the replacement of an existing product with a green one, which limits the natural market advantages that occurred in the past with many technological changes. It then considers the role of government in creating market demand. Governments have always played a role in the deployment of new technologies, but that role is especially important in the case of green technologies.

The capabilities to exploit new scientific and technical knowledge at the firm and country level are cumulative, resulting in incumbency advantages and leading to a significant degree of continuity in technological leadership among first mover firms in countries that industrialized earlier. First movers have the new scientific and engineering knowledge and the capabilities to create new technologies based on this knowledge that are then commercialized in the form of products and processes that can be sold in consumer or industrial market (R&D capabilities) but also the production, marketing, and distribution capabilities. When first movers have solved major problems with commercializing new inventions and are successful, other firms seek to emulate (fast followers) which also tend to be in industrialized countries and have

[1] Circular Economy in Bangladesh's Apparel Industry project, funded by the Danish Fellowship Centre, of which Lindsay Whitfield is a co-investigator.

substantial technological resources to learn rapidly from the leader's experience (Hobday 1995). First movers become the industry's core companies that dominate world markets because they possess several advantages that create barriers to entry for later entrants (Chandler 2004, 2005). These features of first movers—proprietary knowledge, economies of scale and scope, and the strong inflow of income for reinvestment—constitute their *learning base*. The learning base of first movers and fast followers also give these incumbents an advantage in commercializing new technologies, which perpetuated their global leadership.

The innovation studies literature tends to agree that sometimes innovation comes from new entrants and sometimes from incumbents but argues that neither type dominates (Pavitt 1986; Malerba 2007). However, Chandler documents in key industries such as consumer electronics and microelectronics how and why Schumpeter's idea of creative destruction of the monopoly position of incumbents by innovating start-up firms was replaced by the *creative accumulation* by incumbent firms, as Schumpeter also realized by the 1940s, as R&D increasingly took place within big firms (Schumpeter 1954). Similar firm histories are present in Europe. There is strong evidence of creative accumulation and incumbent legacy in all key industries in the twentieth century, which marked a greater trend than creative destruction.[2]

Thus, incumbent firms play a dominant role in shaping the *technological trajectory* in which products of new technical knowledge are commercialized. Incumbents can choose not to commercialize new technologies because they are profitable in the old technologies (Leonard-Barton 1992). Thus, the technological trajectory of an industry is shaped not only by technological progress (new scientific learning), but also by incumbent firms' business strategies and their perception of the 'demand pull': the extent to which consumer preferences and habits create a demand for products based on the new technologies (Dosi 1984). However, the actions of governments in incumbents' countries can also shape the technological trajectory of industries by financing scientific learning, creating an initial market (demand pull) through government contracts, or ending monopolized knowledge through forced licensing of intellectual property (Malerba 1985; Dosi 1984; Chandler 2005).

In sum, we take the approach that the technological trajectory of an industry is shaped by incumbent firm business strategies as well as the actions of incumbent governments—or governments in countries that wish to catch-up by leapfrogging into new technologies—to facilitate the deployment of technological innovation by directing markets. This is because commercializing 'disruptive' technologies requires risky choices on which technology to bet on before it is known which will set the dominant design in the industry; large R&D investments to move from pilot trials to large-scale production processes which requires both scientific and production expertise; and large capital investments in factories and relevant new infrastructure; and building local supply chains. Governments often play a role in creating initial market demand to reach scale and achieve price parity with mature technologies, incentivizing firm investments through forms of de-risking, and providing infrastructure.

In relation to greening industries, initial market demand for products made with green technologies is weak or non-existent because green products are (initially) more expensive than existing brown products. This is because commercializing green technologies requires manufacturing (untested) technologies on a large scale in new production facilities and

[2] Since the 1920s when the chemical and pharmaceutical industries emerged, only two new chemical firms and no pharmaceutical companies were able to enter, by the early 2000s (Chandler 2004: 9).

creating new supply chains and infrastructure. In contrast, similar existing products made from fossil fuels or high raw material and energy use that have lower prices because they operate with established economies of scale, supply chains and infrastructure for distribution and use. It is also because current market prices do not reflect the negative environmental externalities of existing (brown) technologies. Thus, commercializing new green technologies is characterized by relatively high per unit costs, so that innovating firms need to sell their product at a considerable price premium, which tends to deter a demand pull.

Furthermore, the financing requirements of commercializing green technologies is high, as they are typically 'hard' technology, which refers to the asset-intensity of the technology as it involves manufacturing and thus higher capital requirements. (Notably, the cost of capital is another investment cost that increases the per unit costs of green tech firms.) Such capital is difficult for startups to obtain, as financiers may not have confidence that market demand exists and there are many untested technologies on the market as a dominant design has not yet emerged. Over time, if more firms and input suppliers would enter the green technology, economies of scale and scope in input markets and production would increase, and thus price parity to established products becomes easier to achieve. Achieving this situation requires some actors subsidizing the initial process from prototype to large scale industrial deployment. While building the new infrastructure necessary to commercialize the green technology makes sense on a collective industry level, on an individual firm basis this process is costly and entails the risks of sunk costs without knowing the rewards. This is why there is underinvestment in innovation by private investors, below the social optimum (Jansen and Breznitz 2024).

Incumbent firms, which capture considerable market shares in end and/or input markets that are based on established fossil fuel technologies, have the resources and capabilities to make investments to commercialize green technologies but typically do not do so because they enjoy considerable profit margins. This is especially the case in many globalized industries such as textile and apparel, where apparel brands and retailers occupy dominant positions in input markets/sourcing and in end markets. These incumbent firms have grown rapidly based on expanding their brands both in developed and emerging economies, often protected by their intellectual property or tacit knowledge, and they source the relevant (commoditized) inputs at scale and low costs within their supply chains. Therefore, they have few incentives to change the existing division of labor and profits, and thus seek to sustain their profitability with incremental innovation that allows to preserve their dominance in established end markets.

For new firms or established firms from other industries, the initial process of commercializing green fiber technologies requires firms to build a whole range of internal capabilities and manage a number of processes. To reiterate, it requires moving the untested technology from pilot to large scale manufacturing, where the firm internal (scientific) knowledge base needs to be complemented with manufacturing experience, establishing supply chains for new inputs and materials, establishing distribution channels and gaining marketing expertise. It also requires strategic decision on which processes to internalize and which ones to outsource, and it requires taking decisions on the location that has implications for end markets, input sourcing, and regulatory environment.

As start-ups or other firms moving into green fiber technologies do not have all this expertise and financing in-house, none of these commercialization efforts are likely to succeed without two key factors: *inter-firm partnerships* and *government interventions*. Inter-firm partnerships can address challenges related to accessing finance, knowledge, fixed assets and distribution channels. Partnerships can entail a project-specific joint venture to obtain supply chain partners to access key inputs; manufacturing partners that provide machinery and/or manufacturing space; or distribution partners in specific market segments and geographies to enter product markets.

The lack of private financing for firms seeking to commercialize green technologies, especially startups, means that the public sector has played an important role in the cases where it has occurred on a scale large enough to lead to price parity, such as renewable energy and electric vehicles in East Asia (Thurbon et al. 2023; Luethje and Zao 2024). These cases show that government market interventions to create and direct markets for new green technologies can entail supporting research and development that form the basis for the scientific knowledge to be commercialized, i.e. through firms that are spin offs of public research institutes; creating initial market demand, either by some form of public procurement, consumption subsidies or trough banning/phasing out incumbent technology; subsidizing initial production through direct subsidies or tax credit; establishing new infrastructure (both physical infrastructure and trade policy) that enables firms to establish supply chains; and incentivizing inter-firm collaboration (i.e. through establishing vertically-integrated industrial clusters).

Thus, government intervention is often necessary to create markets, tilting the playing field towards the preferred change (Mazzucato 2016). Demand development is necessary. Markets for green technologies hardly exist during development, so success in commercializing green technologies depends on the emergence of market demand. It is hard to see how market demand can be created without government interventions to do so, as illustrated in the next section that explains the context of apparel global supply chains, apparel brands and retailers as the 'incumbent' firms, and the core aspects of government interventions in relation to green fiber technologies which signal regulatory shifts but stop short of creating market demand.

3. GLOBAL FIBER MARKETS, INCUMBENTS AND REGULATORY SHIFTS

The buyer-driven structure of apparel global supply chains poses a problem for the implementation of green fibers. Apparel brands and retailers (called apparel buyers from the supply chain perspective) drive the production practices of their suppliers and decide on innovations of the entire supply chain. Thus, suppliers implement sustainability practices only when required by buyers. While buyers have an oligopsonistic position within global supply chains (there are few buyers compared to suppliers), the degree of competition among buyers in the US and EU end-markets is still very high, as the apparel market is not defined by a high degree of concentration compared to other industries in the US and EU.[3] Intensified competition among these brands and retailers led to relatively few buyers pushing down prices among many suppliers to maintain their markups without increasing retail prices

[3] In 2022, the top ten global buyers accounted for only 10 percent of global market share (Maile and Staritz 2024).

(Abernathy et al. 1999; Milberg and Winkler 2013; Taplin 2014). With the global integration of China and India in the 1990s and the phase-out of the Multi-Fiber Arrangement in the 2000s, the continued reduction of sourcing costs through lowering prices paid to suppliers and shifting more functions and risks to supplier firms became the backbone of apparel buyers' accumulation strategies, resulting in a squeeze on suppliers' profitability. Thus, apparel buyers grew rapidly since the early 2000s by drawing on low-cost supply chains combined with growth in consumer markets due to low prices and product innovations, especially in sportswear (which has a high polyester content), linked to extensive marketing (Maile and Whitfield, forthcoming a).

The dominance of apparel brands and retailers as buyers, combined with extensive fragmentation of apparel supply chains, creates a tough environment for commercializing green fibers. Chains are fragmented because apparel buyers outsource production to many different apparel supplier firms, few of which are vertically integrated with upstream production in fabric, yarn and fibers, and thus source from various textile mills, which source yarn from other mills, and fibers are provided by yet different companies. Apparel buyers are also fragmented in that there are many buyers, and none has a control over the market, making collective action among buyers difficult. Furthermore, apparel buyers control end market access and profit margins along supply chain, capturing the largest value, and it is in their interest to keep it this way.

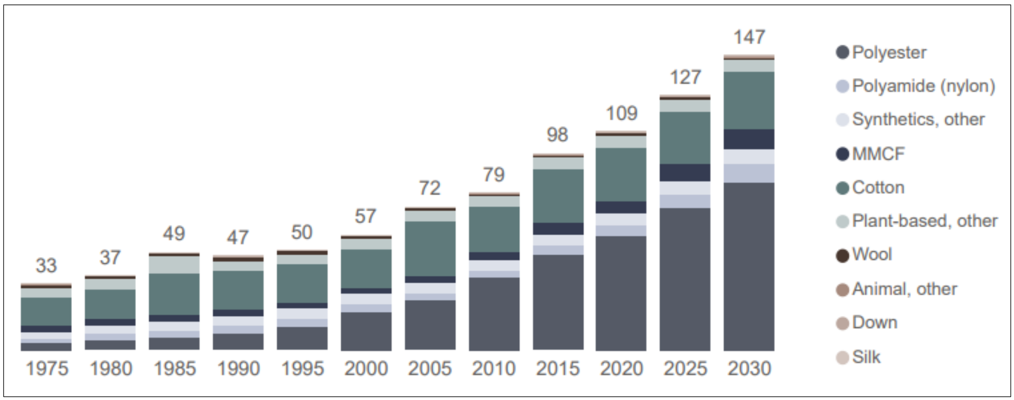
This section has three parts. The first part describes existing global fiber markets and the composition of conventional fibers, which is the context in which green fiber technology firms must enter and compete. The second part describes the key EU and US regulations that attempt to 'green' the global apparel industry by creating new rules for apparel brands and retailers, and then assesses the strength of these regulations in terms of creating market demand for green fibers and supporting the commercialization of green fiber technologies. The third part assesses the responses so far by the top apparel brands and retailers to these regulations.

3.1 Global fiber markets

In 2022, the global apparel industry sourced 116 million tons of fibers.[4] Figure 2 shows that global fiber production doubled since the early 2000s and that this growth was driven by synthetic fibers, predominately polyester. Cotton used to be the dominant material by 1995 but stagnated since the turn of the millennium. Instead, polyester (grey bar at the bottom), and to a smaller extent other synthetic materials, became the sole driver of the industry's expansion. Today, synthetic materials based on petrochemicals account for two thirds of all fibers: polyester (54%), followed by polyamide/nylon (5%), and a range of further synthetic fibers (polypropylene, acrylics, elastane/spandex) that accounted for another 5%. Cotton accounts for 22% of global market share, and a variety of other plant-based fibers (hemp, flax etc.) accounted for another 5%. Man made cellulosic fibers (MMCF), which were predominately derived from wood pulp, constituted 6.3% of the global fiber market. Viscose accounted for 5%, followed by other categories such as acetate, lyocell, and modal, and animal-based fibers accounted for a marginal share (1.6%).

[4] The following data on the global fiber market is based on the Textile Exchange Materials Market Report 2023. https://textileexchange.org/knowledge-center/reports/materials-market-report-2023/?gad_source=1&gclid=EAIaIQobChMIhPTgte2whwMVRZeDBx09UQjvEAAYASAAEgI_YPD_BwE

Figure 1: Global fiber production (million tons), 1975-2020, and estimations for 2030



Source: Textile Exchange (2023: 9)

Polyester was introduced in the 1940s and spandex in 1950s, but their emergence as the dominant material in the global apparel industry was driven by shifting demand and supply conditions in the 1990s. On the demand side, new growth segments such as activewear and outdoor apparel emerged for the mass market in the early 1990s. These product categories required 'performance' textiles that entailed technology functions such as temperature and moisture control or stretchability for which synthetic fibers were needed.[5] Furthermore, the rise of fast fashion strategies with growth based on low-cost volume expansion required the large-scale availability of low-priced fibers. Given the limited elasticity of supply of cotton, synthetic fibers provided the necessary scalability.

This demand from apparel brands and retailers was met by massive investments from Chinese firms in the chemical-fiber textile complex, which meant that synthetic fiber prices remained on a low level since the mid 1990s. Polyester production in China rose from a 12% of global market share in 1990 to 37 % in 2002, while the global polyester market grew from 19 billion pounds to 46 billion pounds during that period.[6] Chinese investments continued in the 2000s, as chemical fiber capacity grew by 18% annually between 2001 and 2008, with chemical polyester capacity increasing more than fourfold in that period.[7] By 2023, China accounted for 72% of chemical fiber production globally.[8][9] China's dominance in chemical fibers was complemented by a vertically integrated chemical fiber-spinning-weaving/knitting complex. Between 2000 and 2022, China's share in global fabric exports rose from 13% in 2000 to 44% in 2022, and in absolute terms, its fabric exports rose from 2.57 billion USD in 2000 to 22.6

[5] https://worksinprogress.co/issue/how-polyester-bounced-back/
Smelik, A. (2023). Polyester: a cultural history. *Fashion Practice*, *15*(2), 279-299.
[6] https://www.fibre2fashion.com/industry-article/3/comparison-of-polyester-industries-in-china-and-india
https://ttu-ir.tdl.org/server/api/core/bitstreams/02dbeb42-415f-4ede-83ab-5617942c23ee/content
[7] Mutuc, M., Hudson, D., Ethridge, D., & Ethridge, M. D. (2010). Inside China's Polyester Fiber Industry: Why the Capacity Overhang?. Texas Tech University, Department of Agricultural and Applied Economics.
https://ttu-ir.tdl.org/server/api/core/bitstreams/02dbeb42-415f-4ede-83ab-5617942c23ee/content
[8] https://www.statista.com/statistics/271653/distribution-of-global-chemical-fiber-production-by-region/
[9] In terms of 'overcapacity' among Chinese synthetic fiber producers, industry publications suggest that utilization rates are fairly high, with an 80% utilization rate in 2020. https://www.just-style.com/news/china-polyester-production-seen-sluggish-in-2020/?cf-view

billion in 2022. By 2022, China accounted 49% and 45% of synthetic and blended fabric exports, respectively.[10] As a result of China's massive production of polyester fiber, the price of polyester decreased from 90 USD cents per pound in 1995 to 50 cents per pound in 1999.[11] The prices does not seem to have increased since then, but data for the period 2005 to 2024 could not be accessed.

Within the existing fiber mix, there were some so-called 'preferred' fibers that had a lower environmental impact than the conventional fibers based on certification processes for production of virgin cotton fibers or man-made cellulosic fibers. The largest was the 'Better Cotton' certification program, which increased its market share of global cotton to 21.5% since its inception in 2005.[12] Better Cotton prohibits the use of certain pesticides and the use of land converted for natural ecosystem. In contrast, organic cotton only had a 1.4% market share within the cotton segment. Of the man-made cellulosic fibers, which come from wood pulp, 63% was certified by FSC[13] or PEFC, which required measures to protect biodiversity in the forests that are certified. Recycled cotton constituted only 1% and recycled MMCF was 0.5% of cotton on the market. In synthetics, preferred fibers included recycled fibers. In 2022, recycled polyester accounted for 14% of all polyester on the market, but 99% of it came from recycled plastic bottles. The recycling share for other synthetic fibers was much smaller: 3% for elastane and 2% for nylon.

In sum, the global fiber market is dominated by low-cost and high availability synthetic fibers mainly produced in an integrated fiber-textile cluster in China, which was also the driver behind supply chains centered on China since the early 2000s that matched the volume and product segment strategies of major apparel brands and retailers. There has been a small shift to 'preferred' fibers, but none of these are circular and deploy green fiber technologies. Therefore, green fiber technology firms face a challenging industry configuration. They must compete with existing synthetic fiber firms that produce commoditized fibers at low prices, high volumes and versatility.

3.2 Regulatory Shifts

The initial institutional disruption in apparel global supply chains was created by key regulatory shifts, and the responses by the apparel industry, notably by major apparel brands and retailers. The evolvement of regulatory shifts can be broadly divided into three different periods. The first period started around the mid 2010s following the Paris Agreement and ended around 2020. During this period, apparel brands and retailers committed on a voluntary basis to long term decarbonization goals and participated in a range of multi-stakeholder initiatives, but with few concrete specifications on how to achieve these goals. As an industry specific implementation of the Paris Agreement, the COP 2018 introduced the Fashion Charter, a framework agreement signed by 109 apparel lead firms including the top 10 apparel

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[10] UN COMTRADE database, June 2024. https://comtrade.un.org
[11] Baffes, J., & Gohou, G. (2005). The co-movement between cotton and polyester prices. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=695383
[12] https://bettercotton.org/what-we-do/defining-better-our-standard/#:~:text=Better%20Cotton%20is%20the%20world%27s,protecting%20and%20restoring%20the%20environment.
[13] https://fsc.org/en/fsc-standards.

buyers.[14] The aim of the agreement was to reduce GHG emissions in operations and supply chains (scope 1,2,3) by 30% until 2030 (from 2015 base line) and to 'net zero' by 2050. Signatories then committed to implement these targets by enrolling into the Science-based Target Initiative to set company-specific decarbonization targets. By 2020, 60 apparel lead firms, including the top 10 lead firms, had submitted goals on emission reductions, and by 2021, this number grew to 142.[15] To implement the targets, more than 250 brands that accounted for 25% of the industry had joined multi-stakeholder initiatives such as the Sustainable Apparel Coalition[16], which offered tools such as the 'Higg Index' where suppliers report on emission and environmental performance, or used the Material Sustainability Index.[17]

From 2020 onwards, however, a set of European regulations were on the horizon, which changed the strategies.[18] The EU regulations focus on establishing a circular economy in the textile industry, setting the path towards recycling textiles into new fibers (textile-to-textile recycling). These EU regulations, which are described in detail below, do not entail interventions to directly create market demand for green fibers. Rather, the implications for fiber markets are mainly related to transparency, reporting and establishing some sort of risk strategy. Thus, the regulations do not create a demand pull, nor have they resulted in creating a circular industry including supply chains.

As a result, apparel brands and retailers responded with strategies to hedge regulatory threats and financial risks in which transparency took a central role. This was the time at which the EU Textile Strategy, Corporate Sustainability Reporting Directive, and Corporate Sustainability Due Diligence Directive were being discussed and the exact content was not clear yet, but the potential situation of penalty fees became a risk. Apparel brands and retailers began to introduce micro-collections of products that used green fibers and their own sustainability labels, as well as set goals on the use of more sustainable fibers. Some brands and retailers invested in green fiber technology firms.

Since 2023, the global apparel industry has also experienced a push back against greenwashing, with NGOs and consumer groups challenging claims by apparel brands and retailers on sustainability claiming that they lack substance. Furthermore, despite the initial hype, brands and retailers have not committed to large scale offtake agreements for green fibers with green fiber technology firms. In fact, major brands and retailers scaled down their sustainability claims and expanded the time horizon on their decarbonization goals.[19] Therefore, the EU regulatory shift that initiated market interest in a range of green fiber technology firms has not yet translated to clear market signals on specific fibers.

[14] UNFCCC (2022). About the Fashion Industry Charter. https://unfccc.int/climate-action/sectoral-engagement/global-climate-action-in-fashion/about-the-fashion-industry-charter-for-climate-action
[15] SBTI (2021). Progress Report. https://sciencebasedtargets.org/reports/sbti-progress-report-2021
[16] https://cascale.org/resources/publications/sac-a-decade-in-review/#:~:text=A%20decade%20after%20we%20launched,an%20option%20to%20delay%20action.
[17] https://www.just-style.com/news/sac-rebrands-to-cascale-promises-era-of-positive-impact-in-consumer-goods/?cf-view
[18] https://www.bcg.com/publications/2023/driving-profitability-with-raw-materials-in-fashion
[19] https://sourcingjournal.com/sustainability/sustainability-compliance/greenwashing-fast-fashion-hm-conscious-collection-primark-cares-zara-greenpeace-435701/; https://www.just-style.com/news/hm-group-norrona-under-fire-in-norway-over-environmental-claims/.

The most significant policy package is the EU Strategy for Sustainable and Circular Textiles, which is the industry specific implementation of the EU's Circular Economy Action Plan. The strategy was adopted in March 2022 by the EU Commission and entails the explicit aim to ensure that "all textile products placed on the EU market are durable, repairable and recyclable, to a great extent made of recycled fibers", to "end fast fashion", and "make repair and reuse business model profitable'.[20] The concrete implementation of these goals is pursued via a set of policies which have been adopted and are currently in a multi-year implementation phase that includes the concrete specifications of the legislations. We describe the key policies that target fiber use in apparel global supply chains and then summarize their aims, concrete requirements, and implications for fiber sourcing in Table 2.

The *Ecodesign for Sustainable Products Regulation* (ESPR) adopted in 2022 establishes a framework for setting ecodesign requirements. The implementation phase began in 2024, which includes preparatory studies, impact assessments and consultation with stakeholders, which are set to translate into an enforcement by 2027. The ESPR aims to set performance and information requirements on durability, reusability, upgradability and reparability, and resource efficiency. However, the concrete performance requirements have not yet been specified. There are two further key building blocks on transparency. First, the Digital Product Passport requires a scannable QR code or other means of identification that displays standardized and detailed information on products inputs, the supply chain and sustainability claims. Second, the ESPR aims to abandon the destruction of unsold goods by brands and retailers selling in the EU, by requiring them to provide information on the destruction of garments and provide reasons.[21] While there is not yet any evidence that the ESPR will culminate in banning certain fiber inputs or set definitive minimum recycling quotas, it can be expected that it will raise requirements for transparency measures and standardize their communication.

The *EU Green Claims Directive 2023* aims to address unsubstantiated sustainability claims on textiles. It was catalyzed by a study commissioned by the EU in 2020, which concluded that more than half of sustainability claims of 230 labels across a range of products were 'vague, misleading, or unfounded' given the lack of any form of verifiability.[22] In essence, the Directive seeks to require detailed specification on voluntary claims made by brands and retailers regarding recycling content or emission levels for the fibers that are used. The verification can be based a life cycle analysis that is verified by an independent third party.[23] As a consequence, the majority of existing in-house ecolabels that have been introduced by major fashion brands in recent years, such as H&M's Conscious Choice or the sustainability flag by Zalando, will be banned in their current form.[24]

[20] https://environment.ec.europa.eu/strategy/textiles-strategy_en
[21] https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/sustainable-products/ecodesign-sustainable-products-regulation_en
[22] https://www.bluesign.com/zh/the-european-commision-green-claims-directive/#:~:text=The%20European%20Commission%27s%202020%20study,were%20unsubstantiated%20by%20verifiable%20evidence.
[23] https://www.2bpolicy.eu/news/substantiating-green-claims; https://environment.ec.europa.eu/topics/circular-economy/green-claims_en; https://environment.ec.europa.eu/topics/circular-economy/green-claims_en
[24] https://sourcingjournal.com/sustainability/sustainability-compliance/hm-asos-zalando-greenwashing-eu-green-claims-directive-higg-msi-pef-422522/

The *Waste shipment regulation* aims to prohibit unmanaged exports of textile waste to third countries. The EU Commission approved the new regulation in 2024, which will come into force in 2027. As a result, apparel brands and retailers that sell in the EU will need to demonstrate a 'proper management' of waste that is shipped to recipient countries. The Waste shipment regulation aims to encourage the recyclability of fibers in Europe, but negotiations over how exactly to define waste are ongoing: when does it start to be waste and end to be waste.[25]
The first definition of EU regulation said that waste ceases to be waste when it is spun again, seemingly to support (re)building the textile industry in Europe. This definition disadvantages green fiber technology companies that only produce a material that can be spun into fibers or the fibers themselves, but must sell it to yarn producers, most of which are not located in Europe. A new definition of waste is expected as negotiations continue.[26]

The *Waste Framework Directive* includes the *Extended Producer Responsibility* (EPR), which means that apparel brands will have to pay a fee to finance the infrastructure for collection, resorting and recycling of textiles, which member states will put in place by 2025. The EPR further prohibits the destruction of unsold goods without the ensuring of re-use. As the fees are expected to be 'eco-modulated', which means that brands and retailers using recyclable fibers can be expected to entail cost savings, but it is not clear yet.[27] This EU directive has the greatest potential to create market demand by imposing fees on apparel brands and retailers, but which can be reduced or offset by using recycled fibers, leading to increased demand by brands and retailers for recycled fibers. Perhaps because of this, the Directive is still to be negotiated and thus its contents and enforcement date are not yet clear.

The revision of the *Textile Labelling Regulation* was announced in 2023 and envisions an inclusion of new fiber and of recycled fibers into uniform labelling requirements in garments. It is implied that consumers will be able to differentiate garments that are based on green fibers vis-à-vis fibers that are derived from recycling of PET chips from plastic bottles or virgin materials, which is expected to encourage the sourcing of circular fibers.[28]

The Corporate Sustainability Due Diligence Directive obliges EU-based firms to identify potential negative impacts on human rights and the environment and to take measures to prevent or mitigate these impacts. Similar national regulations, such as the one Germany introduced in 2024, are likely to be superseded by EU law. This Directive includes civil liability, and all tiers of the supply chain, and applies to EU based companies with more than 1000 employees, EUR 450 million turnover and non-EU firms that have +450 turnover in EU. Due diligence requires risk analysis by firms and traceability, but it has no clear implications for fiber content and may only lead brands and retailers to source certified preferred fibers that are traceable.[29]

[25] https://environment.ec.europa.eu/topics/waste-and-recycling/waste-shipments_en
[26] Interview with a green fiber technology company, 9 August 2024.
[27] https://sourcingjournal.com/sustainability/sustainability-compliance/european-parliament-eu-waste-framework-directive-textiles-epr-495128/
[28] https://single-market-economy.ec.europa.eu/sectors/textiles-ecosystem/regulation-eu-10072011_en
[29] https://www.bcg.com/publications/2023/driving-profitability-with-raw-materials-in-fashion; https://commission.europa.eu/business-economy-euro/doing-business-eu/sustainability-due-diligence-responsible-business/corporate-sustainability-due-diligence_en

The EU's Corporate Sustainability Reporting Directive aims to ensure that investors and other stakeholders have access to the information they need to assess the impact of companies on people and the environment and for investors to assess financial risks and opportunities arising from climate change and other sustainability issue. It entered into force in January 2023 and requires all listed firms and larger non-listed firms to report emissions, set targets and show progress verified by an independent third party. It applies to EU firms that have 150 million turnover or non-EU firms that generate more than 150 million in EU.[30] Similar targets on corporate transparency were introduced in the US with the SEC Climate Disclosure Rule, which requires US-based publicly listed apparel lead firms to publish sustainability reports GHG 1/2/3 emissions, risk assessments, and transition strategies. The Financial Service Agency in Japan will introduce similar requirements on climate reporting for listed firms in 2024. [31] Again, the likely impact will be a focus on transparency and a shift to preferred fibers.

In the US, legislation targeting apparel supply chains started much later than in the EU, so their implications are not yet clear, but some of the legislation could impact fiber sourcing. On a state level, a few states have announced apparel related legislations. The measures in New York and Washington focus on due diligence, whereas legislation in California is about extended producer responsibility. The New York Fashion Act, which began in 2022, is similar to the EU Due Diligence Directive but with focus on fashion firms with more than 100 million USD revenue, and with a penalty of up to 2% of revenue. It requires fashion sellers to be accountable to standardized environmental and social due diligence policies and establishes a fashion remediation fund.[32] The California Responsible Textile Recovery Act of 2024 will require firms that sell in California (manufacturers and brands/retailers with +1 million sales) to implement and fund a program to facilitate the reuse, repair, and recycling of clothing and textile fibers.[33] Under the platform, a Producer Responsibility Organization would manage the collection, sortation and recycling of the recovered goods.[34] The Washington House Bill requires fashion manufacturers to establish, track, and disclose progress towards due diligence and environmental performance targets from 1 January 2027.[35] The US federal government is considering the US Americas Act, a bipartisan bill that includes over $10 billion loans and 3 billion grants in incentives for circularity across apparel, footwear, accessories, and home linens. Funding is also available in grant or loan form to businesses that provide the inputs, like chemicals, solvents and machinery necessary for transporting, collecting, mailing

[30] EC, 2022 https://finance.ec.europa.eu/capital-markets-union-and-financial-markets/company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en

[31] https://finance.ec.europa.eu/capital-markets-union-and-financial-markets/company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en
https://www.morganlewis.com/pubs/2022/12/japan-introduces-mandatory-esg-disclosures-for-public-companies

[32] https://www.nysenate.gov/legislation/bills/2023/S4746/amendment/A; https://atmos.earth/in-new-york-and-beyond-why-the-fashion-act-matters/

[33] https://sd29.senate.ca.gov/news/press-release/newmans-landmark-textile-recycling-bill-advances-california-assembly#:~:text=The%20bill%2C%20also%20known%20as,of%20clothing%20and%20textile%20fibers.; https://sourcingjournal.com/sustainability/sustainability-news/california-responsible-textile-recovery-act-bill-recycling-apparel-epr-sb-707-515921/

[34] https://sd29.senate.ca.gov/news/press-release/newmans-landmark-textile-recycling-bill-advances-california-assembly#:~:text=The%20bill%2C%20also%20known%20as,of%20clothing%20and%20textile%20fibers; https://sourcingjournal.com/sustainability/sustainability-news/california-responsible-textile-recovery-act-bill-recycling-apparel-epr-sb-707-515921/

[35] https://www.just-style.com/news/washington-joins-california-new-york-with-fashion-regulation-bill/

back, sorting and pre-processing textile products. The Act emphasizes textile recycling and targets supply chains across North, Central and South America.[36]

China's government has also enacted legislation recently regarding textile. In 2022 there was an announcement of guidelines that aim to recycle 25% of textile waste by 2025.[37] It also passed a law that aims at emulating the EU's circular textile strategy, but it is focused on recycling within China for the Chinese market and not fiber production for global export markets.

Table 1: Key legislations affecting global fiber markets

Regulation	Aim and evolvement	Concrete requirements	Expected implications for sourcing green fibers (strong to weak)
EU Textile Strategy			
Ecodesign for Sustainabale Product Regulation	Improve circularity and energy performance (several goods including textiles) 2022 Adoption proposal 2024-27 implementation in working groups 2027: Enforcement	-Establish framework for ecodesign requirements -Digital product passport -Information requirements and justification on destruction of unsold textile	Weak -Higher and more standardized transparency requirements on fibers and their production, supply chain stages, and so on.
Green Claims Directive	Make green claims reliable, verifiable and comparable 2020: Study found lack of substance of sustainability claims 2020: Adoption proposal 2024: Enforcement date	-Criteria on sustainability claims – detailed specification on recycling or emission reduction claims -Verification of claim by third party	Weak -voluntary claims on 'more sustainable' or 'recycled' fibers need to be substantiated
Waste shipment regulation	Prevent illegal waste shipment, including textile 2006: first version 2021: adoption proposal for revision 2024: Approval revision 2027: Enforcement	-firms exporting waste from EU need to demonstrate 'proper management' in the recipient country -verify with independent audit	Weak -could incentivize the use of more recyclable fibers, to avoid waste management
Waste Directive Framework and Extended Producer Responsibility	Introduce harmonized and mandatory EPR 2023: Proposal for revision Directive not yet adopted. Enforcement date is 18 months after the Directive is adopted.	-Firms selling in EU need to pay fees for collection, resorting and recycling infrastructure - Fee based on 'eco-modulation': differentiation by material type	Moderate -fee differentiation could incentivize more recyclable fibers
Textile Labelling Regulation	Include new fiber types and recycled fibers into labelling	-Introduction of a single and uniform set of rules on	Weak -shift responsibility to

[36] https://recoverfiber.com/newsroom/upcoming-legislation-circular-fashion-usa#:~:text=The%20Americas%20Act%20is%20a,US%2C%20but%20specifically%20from%20China.https://www.businessoffashion.com/news/sustainability/americas-act-us-manufacturing-textiles-circularity-legislation/; https://sourcingjournal.com/sustainability/sustainability-news/americas-act-textiles-apparel-circularity-recycling-14-billion-act-onshoring-498324/; https://www.voguebusiness.com/story/sustainability/a-new-us-bill-the-americas-act-incentivises-circular-fashion-in-a-bid-to-compete-with-china
[37] https://www.textiletechnology.net/technology/news/china-recycling-of-25--of-all-textile-waste-by-2025-32004

Regulation	Aim and evolvement	Concrete requirements	Expected implications for sourcing green fibers (strong to weak)
	requirements 2011: Regulation labelling of fiber composition 2023: Announcement of plan to revise labelling regulation to include new fiber types	labelling for different fibers	consumers to create market demand for green fibers
USA			
Fashion laws in US states	New York Fashion Act: Establish Due Diligence Process for Fashion brands operating in NY 2024 Washington House Bill 2068: Establish due diligence for fashion brands and manufacturers (announced 2024, in force 2027) California Responsible Textile Recovery Act: Establish Extended producer responsibilities in apparel supply chains (2024)	Report on emission, material used and wages of workers Track, and disclose progress towards due diligence and environmental performance Brands and producers fund a program to facilitate the reuse, repair, and recycling of clothing and textile fibers	Transparency Transparency Weak: EPR could incentivize market demand for recyclable fibers
Americas Act	Establish growth of regional circular textile industry	Works with financial incentives: USD 14 billion grants and loans 15% tax break for firms working in textile reuse and recycling USD 1 billion R&D/innovation fund on recycling	Financial incentives help to provide textile to textile recycling firms and logistics provider with patient capital, to bridge profitability gap At the same time no provision for brands/retailers to source recycled fibers

Source: Created by the authors.

3.3 Responses of major apparel brands and retailers

These new regulations in the EU market, and a lesser extent in the US, have implications for the business and sourcing strategies of global apparel brands and retailers are wide-ranging, especially in relation to transparency and verifiability as well as waste management. The policies require increased and standardized transparency for the fiber mix and related environmental impact. In terms of waste management, existing practices of discarding unsold inventory will be prohibited. At the same time, the regulations neither ban certain fibers nor require specifications of the type or level of fibers that need to be used. As a result, the regulations do not directly create market demand for green fibers. Instead, the major apparel brands and retailers are hedging the regulatory risk in terms of transparency through a gradual shift in their fiber sourcing strategies towards 'preferred' fibers.

Table 3 lists the material decarbonization strategies of the largest ten apparel buyers by revenue, which collectively command a sourcing volume of more than USD 200 billion. It shows that the ambitions of these apparel buyers to shift their raw materials sourcing towards low carbon fibers varies in terms of scale and the types of lower carbon fibers they seek to introduce. It shows that all major brands and retailers have committed to increase the use of fibers with less environmental impact than conventional fibers, but these firms do not state whether and which kinds of fibers they seek to include. The material strategies of Inditex, H&M, Puma and PVH can be regarded as the most ambitious, as these firms seek to cover 100% of their raw materials with more sustainable fibers by the end of this decade. GAP and VF announced strategies that cover all fibers within a particular fiber segment (cotton, polyester), but have excluded other fiber types from their aims (other synthetics, man-made cellulosic fibers). Lululemon aims to cover 75% of their materials with more sustainable raw materials, while Nike and Fast Retailing aim for 50%. The strategy of Adidas is based on a vague formulation that entails producing '9 out of 10 products' from more sustainable materials, and therefore can be regarded as the least ambitious strategy.

All material decarbonization strategies involve shifting the fiber portfolio fully, or larger shares, to 'preferred' or 'more sustainable' sources. They presuppose that these preferred materials are different from conventional fibers in that they emit less carbon and have a lower environmental impact in terms of chemicals used and water pollution. In terms of the specific definition that differentiates 'preferred' from conventional materials, 7 out of 10 of the apparel buyers rely on the definition given by Textile Exchange, with the remaining 3 buyers providing no detailed specification (Fast Retailing, Lululemon, VF). The Preferred Fiber and Material Matrix by Textile Exchange differentiates fibers in a given materials class in terms of the environmental impact with scores between 0 (no difference to conventional materials) to 100 (strongest differentiation to conventional fibers) based on a number of criteria related to the fiber's climate, water, chemistry and land use.[38] The preferred fiber list includes a number of certification schemes for virgin raw materials (such as Better Cotton Initiative cotton or FSC wood pulp), and it contains recycling materials definitions that set very low thresholds for 'recycled' material to be counted as such. For example, polyester certified by the Recycled Claim Standards requires a minimum recycling content of 5%.[39] In the Global Recycling Standards, the minimum threshold for recycling content is 20%, which can be fulfilled by using PET chips from plastic bottles.[40]

None of the material strategies of these apparel buyers includes concrete goals on the share and specific type of textile-to-textile recycling or bio-based fibers. Inditex is the only top ten buyer that explicitly mentions 'next generation fibers' (what we call green fibers) in its envisioned material mix by 2030, stating that it estimates that 25% of the more sustainable fibers could come from next generation fibers. Four of the top ten apparel buyers have taken equity investments green fiber technology companies, with H&M and Inditex having the most investments. These two global apparel retailers also have committed to large scale offtake agreements on recycled or biobased fibers: Inditex with USD 170 million cumulatively, and H&M with USD 600 million.

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[38] https://pfmm.textileexchange.org/

[39] See p. 10 on recycling definition https://textileexchange.org/app/uploads/2021/02/Recycled-Claim-Standard-v2.0.pdf

[40] See p. 6 on recycling definition https://textileexchange.org/app/uploads/2021/02/Global-Recycled-Standard-v4.0.pdf

We conclude that the predominant response of major apparel buyers and retailers to the EU regulatory shift has been towards preferred fibers, which have lower environmental impact that conventional fibers, but much higher than fibers from textile-to-textile recycling or bio-based fibers. The upcoming regulations have therefore sparked the interest of apparel brands and retailers in green fibers but have not caused a major shift in the sourcing patterns of lead firms. Therefore, the regulation was necessary to attract interest in the new green fiber technologies and the firms pioneering them, but it has only resulted in experimentation through 'micro collections' as well as a number of equity investments into green fiber startups. The regulatory changes were insufficient to culminate in a strong demand pull in terms of large-scale orders for green fibers, and the major apparel buyers are willing to pay an initial premium for these green fibers.

Table 2: Material decarbonization strategy (2023), Top 10 apparel buyers by revenue

Buyer	Revenue 2023 (million USD)	Materials strategy (year and fiber mix)	Specifications	Equity investments // Take off agreement // Consortia membership (July 2024)
Nike	51.326	2025: 50% 'preferred' materials – 'sustainable or recycled materials' based on textile exchange Status: (48% in 2022, 45% in 2023)		
Inditex	39.001	2030: 100% textile products that use lower-impact materials. This could entail: 25% 'next gen fibers' 40% from conventional recycling. 25% will come from organic or regenerative agriculture. 10% preferred materials Status: 68% preferred materials by 2023		Equity: Circ Offtake agreement: 100 million (Infinited), 70 million (Ambercyle)
Adidas	23.684	2025: 9 out of 10 with preferred materials		Consortium: Bolt Threads
H&M	22.604	2030: 100% recycled or more sustainable (preferred) fibers 2025: 30% recycled fibers.		Equity: Syre, Werewool, Infinite, Renewcell (restructured), Ambercycle Keel labs, Kintra, etc (total 27) Take off agreement: 600 million (Syre), Infinited, Circ (amount unknown)
Fast Retailing	18.997	2030: 50% of all materials recycled or low GHG materials	No specification on low GHG materials	Equity: Infinited
GAP	14.889	2030: Use 100% more sustainable cotton by 2030 100% polyester from recycled sources (PET) 2030 (15% in 2023)	Cotton includes regenerative, organic, in conversion to organic, recycled, and U.S. Cotton Trust Protocol verified cotton	Offtake agreement: Ambercyle (amount unknown)

Buyer	Revenue 2023 (million USD)	Materials strategy (year and fiber mix)	Specifications	Equity investments // Take off agreement // Consortia membership (July 2024)
VF	10.455	2026: 100% cotton sourced is grown in the U.S., Australia or under a third-party cotton growing scheme by 2026 (currently at 88% in 2023) 50% of polyester will originate from recycled materials by 2026 (currently 40% in 2023)	No further specification	
Lululemon	9.619	2025: 75% sustainable materials, including recycled, renewable, regenerative, sourced responsibly, or some combination thereof, and/or are manufactured using low-resource processes.	No further specification	Equity: Geno (tbc), Samsara Eco Consortium: Bolt Threads
Puma	9.508	2025: 100% cotton, polyester, leather and down feathers as well as paper and cardboard from sustainable sources. Increase recycled polyester use to 75% by 2025	Bluesign certification (less harmful chemicals) counts as 'sustainable' polyester The Annuel Report 2023 does not define 'recycled polyester'	
PVH	9.218	2025: 100% of sustainable (certified or organic) cotton and viscose 2030: 100% sustainable polyester		

Sources: Data on raw material strategies was collected in corporations' sustainability impact reports (FY 2023) or websites.
Nike: https://about.nike.com/en/impact?filter=Responsible+Sourcing;
Inditex, p. 239: https://static.inditex.com/annual_report_2023/en/Inditex_Group_Annual_Accounts_2023.pdf;
H&M: https://hmgroup.com/sustainability/circularity-and-climate/materials/#:~:text=How%20we%20work%20with%20materials,30%25%20recycled%20materials%20by%202025.;
Fast Retailing: https://www.fastretailing.com/eng/sustainability/products/procurement.html;
GAP: https://www.gap.com/page/gap-for-good?cid=1086537#:~:text=Of%20goal%20reached-,Our%20Goal,to%20improve%20cotton%20farming%20globally.
https://www.gapinc.com/en-us/values/sustainability/enriching-communities/raw-materials-and-product;
VF:https://d1io3yog0oux5.cloudfront.net/_8976ca631b4350ebfb8ce74b4ebdc137/vfc/files/documents/Sustainability/Resources/VF_FY2023_Environmental_Social_Responsibility_Report_FINAL.pdf
Lululemon: https://shop.lululemon.com/story/product-sustainability
Puma: https://annual-report.puma.com/2023/en/downloads/index.html
PVH: https://www.pvh.com/-/media/Files/pvh/responsibility/PVH-CR-Report-2022.pdf

4. GREEN FIBER TECHNOLOGIES AND GREEN TECH FIRMS

There are currently 129 firms that pursue commercialization of green fibers. We grouped these firms into three categories based on the type of meta-technology:

(1) *Bio-based fibers*: products wholly or partly derived from biomass, such as plants, trees or animals.
(2) *Regenerated cellulosic fibers*: recycling of cellulose rich materials, including but not limited to recycled cotton fibers.
(3) *Textile-to-textile recycled synthetic fibers*: recycling of polyester or other petrochemical fibers from pre- and post-consumer textile waste.

The type of meta-technology determines the type of feedstock that is required and the manufacturing process as well as the textile fiber segment that firms seek to replace (within the apparel industry) and with respect to the broader application range (outside the apparel industry). Thus, the opportunities and challenges to commercializing green fiber technologies can differ across firms depending on the meta-technology.

4.1 GREEN FIBER TECHNOLOGIES

For bio-based fibers, we use the classification provided by Fashion for Good, which distinguishes between biosynthetic and biofabricated fibers.[41] *Biosynthetic fibers* are based on synthetic (in the sense of being man-made) polymer materials that are derived in part or wholly from bio-based molecules. Biosynthetic processes can be used to create biobased 'dropins' for existing petrochemical derived materials, and thus used as an alternative process to create synthetic a polymer that is chemically similar or identical to polyester. These compounds can be either created through biomass input, or via a living microorganism that performs this process. Specific methods include for example the fermentation or sugar or the catalytic conversion of biomass to create precursor chemicals for synthetic polymers.

Biofabricated fibers are produced by living cells and microorganisms such as bacteria, yeast and mycelium. In essence, organisms are cultivated to produce new material structures. Biofabrication can be either pursued via producing biofabricated ingredients, where living cells and microorganism produce complex proteins, which then require further chemical or mechanical processing to create new macroscale material structures. Examples for biofabricated ingredients are complex proteins such as fermented recombinant silk which has to be spun into fiber. Another route is to pursue bioassembly, where living microorganisms perform the self-assembly of macroscale structures. Examples are lab grown leather based on mycelium, which creates threadlike hyphae forms, or microbial fermentation, which forms ready cellulose sheets. Notably, both processes of bio-fabrication allow for a cultivated novel structure and tunability of materials, which is important for developing new and different quality applications within and outside textile fibers.

Using these technologies for textile fibers has only evolved in the 2000s and particularly in the 2010s. Many founders of these firms have a technical background in bioengineering or biochemistry and have worked and experimented on that particular technology for several

[41] https://reports.fashionforgood.com/wp-content/uploads/2020/12/Understanding-Bio-Material-Innovations-Report.pdf

years prior to trying to produce it for apparel products. In bio-based fiber technologies, the innovation is often in both the base technology (in biotech) and its application to apparel products. However, this also means that the proof-of-concept stage can be long, and the technology is very untested, and thus high risk.

Textile-to-textile recycling of petrochemical synthetic fibers such as polyester or polyamide is based on chemical or advanced thermal recycling procedures, break down the polymers into monomers and subsequently repolymerize these. The basic chemical recycling methods have existed for a while: hydrolysis, methanolysis, and glycolysis (the most common type of recycling for polyester).[42] It is the application to textile that is new, which comes with a number of issues that have to be solved. Waste textile is never pure. For example, clothing fabric is made with yarns that blend different fibers, which need to be separated. The chemical recycling process has to address dyed fibers. Designing a process to handle all of these aspects of textile waste is challenging. This issue is one motivation behind the digital passport in EU regulations, as it will let recycling companies know exactly what is in the textile waste and thus make recycling easier. Innovations and patents centre on designing these processes, but a core challenge is accessing feedstock as textile recycling infrastructure has to be created. This is another objective of the EU and more recent US regulations. As such, it is only very recently that green tech firms emerged that aim to commercialize polyester textile chemical recycling technologies. The costs and risks are high, while the costs of virgin polyester fibers are very low, making it hard to achieve price parity.

Regenerative cellulosic fibers are based on the chemical recycling of cellulose-rich materials such as agricultural waste and cotton-rich textile waste that creates a pulp that has to be spun into a fiber. The initial firms used the existing technology for producing lyocell, which evolved from the process of producing viscose with wood pulp that emerged in the 1880s based on chemicals and made the fiber production process more environmentally friendly. Lyocell production does not use chemicals to dissolve the cellulose from wood pulp but a solvent, and then uses a closed loop production system to spin the fiber. The lyocell patent expired and thus any firm can use this process. This lyocell process is also used to produce fibers from cellulosic material produced in other ways, such as microbial cellulose (which is generated by microbes in agricultural waste).

Many of the firms producing regenerative cellulose from recycled cotton textile waste are firms that used to produce wood pulp products or firms that produce viscose or lyocell using wood pulp. These firms are predominantly located in Finland and Sweden, which had forestry industries, or countries like India and Turkey with textile industries and a history of viscose production. However, the paper industry has gone down, and there is a sustainability issue with cutting more trees. Thus, firms with capabilities in making regenerative cellulose have shifted to using them to create pulp out of recycled cotton-rich textile. Some firms still produce viscose and lyocell from wood pulp but mix in pulp made from recycled cotton textile waste.

Thus, the technology for spinning pulp is not new. What is new is the application to cotton waste textile—to making cellulose from a different feedstock, and this application is clearly in response to EU regulations that put an emphasis on reducing textile waste through textile-to-

[42] Textile Exchange, The Future of Synthetics, April 2024, p. 15. https://textileexchange.org/app/uploads/2024/04/The-Future-of-Synthetics.pdf

textile recycling. The innovation comes in how the cotton textile waste is treated to make it suitable for using the spinning process for viscose or lyocell, or other technologies such as carbamation.

Currently, 100 percent lyocell cannot substitute for 100 percent cotton; instead, it has to be blended. Lyocell is stronger than cotton, so it improves the performance of the fabric. Currently blends are only 20 percent recycled lyocell (regenerative cellulose made with recycled cotton textile) and 80 percent virgin cotton without changing the feel of the fabric at all. The exact technologies of fiber technology firms in the regenerative cellulosic category vary, with implications for the extent to which they can substitute for cotton. However, it is also a function of continuous R&D in fiber development in the production process at scale. More research and development in fiber production is needed before regenerative cellulose can be used as a direct substitute for virgin cotton.

4.2 Mapping of green fiber technology firms

Table 4 provides an overview on all firms that aim to commercialize green fibers. The majority of these firms began to pursue commercialization of their technologies around the mid-2010s: 76 of the 129 of firms were founded after 2014. Even many firms that were founded earlier only decided to focus their technology for use in the textile fiber market in the mid-2010s. For example, bio-based firm Geno was founded in 1998 but initially worked on plant-based glycol for cosmetics, and its bio-based nylon was only launched in 2021. Similarly, firms like MycoWorks or Circ were founded in 2013 and 2011, respectively, but the direction of their commercialization with textile industry was only taken towards the end of the 2010s.

Table 3: Overview on firms aiming to commercialize circular fibers, July 2024

Meta Technology group	Specific sub-technologies	Number of firms	No. firms classified as start-ups	No. firms subsidiaries of established players	Firms that claim commercial scale*	Total VC funds flowed into firms (million USD)
Bio-based	Biosynthetic	62	32	30	36	1.180
	Biofabricated	38	31	7	19	997
Regenerative cellulose		12	7	5	8	67.6
Recycled polyester and polyamide		17	11	6	12	395.06

Notes: *The data for assessing commercial scale is the self-reporting of firms on their websites, and not a third-party assessment.

A majority of the firms are producing bio-based fibers, especially biosynthetic where the number of firms is larger than any of the other categories due to the large number of firms being subsidiaries of established players. In other words, there is a large number of incumbent firms that have invested in biosynthetic green fibers. Of the total 62 biosynthetic firms, almost half are subsidiaries of incumbent firms (30), which is higher than in any of the other technology categories. This is an interesting insight, but thus far we cannot explain why this is the case, and will therefore look into it in future research. Furthermore, more firms in biosynthetic technology claim to be operating at commercial scale than in any other category. We thought that there might be a correlation with the large number of incumbent firms, but the data in the mapping do not show a correlation in that respect. Again, we need further research to understand why more firms are at the commercialization stage. We only have one biosynthetic firm in our 10 firm case studies below, so we cannot gleam much about these issues from that one case, which is of an incumbent firm that has not reached commercial scale yet.

The bio-based fiber technology firms have attracted the highest cumulative venture capital funds, equaling 2.177 billion USD. However, a large part of these funds were concentrated in a small number of start-ups, such as Bolt Threads (more than USD 300 million) and MycoWorks (USD 350 million). There were 17 firms using chemical recycling technologies for polyester and polyamide, obtaining USD 395 million in cumulative venture capital funds. Only 12 firms were using regenerative cellulose technology, which collected USD 67 million in venture capital.

While the table shows that more than half of the firms in each meta-technology have announced that they have moved from pilot to commercial scale, this should be taken with some caution as they use varying definitions of ‘commercial scale’. Nevertheless, one trend is clear. The majority of firms in polyester textile recycling announced commercialization targets only in recent years, but their scaling plans are more ambitious compared to firms operating with regenerative cellulose and particularly bio-based technologies.

4.3 Case studies of green fiber technology firms

In this section, we analyze the commercialization strategies of 10 circular fiber producers We chose firms across all three meta technologies:

- Biobased (3)
  - Biofabrication: Spiber, Bolt Threads, MycoWorks
- Regenerative Cellulose (4)
  - Circulose, Spinnova, Infinited, AeoniQ
- Polyester textile-to-textile recycling (3)
  - Syre, Circ, Ambercycle

Based on the mapping exercise, these firms are among those that received the highest interest in terms of announced sourcing volumes and venture capital funding, based on the mapping exercise. We present the ten case study firms, focusing on the technology, the firm history, and the commercialization strategy, including financing, supply chain and production, and distribution. These factors are summarized in Table 6 at the end of the section.

1. **Spiber (biofabrication technology)**

Japan-based Spiber was founded in 2007 as a spin off from the Institute for Advanced Biosciences at Keio University. Its technology is centered around a ‘brewed synthetic protein platform’, in which Spiber uses microbial fermentation processes to convert agricultural feedstocks, predominantly sugarcane and corn, into fermented polymers for fibers that according to Spiber can serve as a biodegradable substitute for wool, leather, fur, cashmere and silk as well as plastic-based materials. The polymer’s characteristics are tunable, meaning that with a few tweaks it can take on the performance and feel of knits, wovens, fleece, leather or fur.[43]

Spiber initially focused on creating a substitute for spider silk, which is a high value fiber given its material strength in combination with flexibility. However, its 'Qmonos' material did not succeed, given that the underlying fibrion protein causes super shrinkage when becoming wet, inhibiting the stability of garments. Spiber fixed the issue by the amino acid sequence features causing shrinkage from the fibroin gene and rebranded Qmonos into 'Brewed Protein'.[44] By 2021, the ISO had recognized the synthetically structured Brewed'Protein fibers as a sperate material category.

Spiber received large sums of equity finance for its Brewed Protein fiber, backed by intellectual property rights. In 2022, it generated proceeds worth USD 313 million. The funding round was led by US private equity firm Carlye and included investors such as Kansai Paint, Baillie Gifford, and Fidelity Investments.[45] In April 2024, Spiber raised another 65 million USD for scaling, bringing the total amount of capital injections to USD 489 million.[46]

Spiber's brewed protein fiber is included in a number of pilot collections of 15 brands in the higher price segment, notably North Face, Goldwin and Woolrich. For instance, American sportswear brand Goldwin launched the first Brewed Protein sweater at $800. Spiber also launched a prototype with North Face called the moon parka, and a sweater with UK based Pangaia. At the same time, Spiber aims at expanding the application of the brewed protein platform beyond the apparel industry such as for Shiseido in cosmetics and for Toyota in car seats.

Spiber began to invest in a first factory in Rayong, Thailand that became operational in 2022, producing several hundred tons output per year.[47] In 2023 it partnered with US commodity trader Archer Daniels Midland (ADM) to expand production of Brewed Protein polymers in a factory in Iowa, US. The two companies stated that they sought to combine their expertise, with Spiber bringing in the technology and ADM providing the feedstock and existing capital assets. The brewed protein polymers will be produced by ADM in the U.S. using plant-based dextrose as a feedstock and then shipped to Spiber's downstream facilities where they will be processed into an array of materials, primarily fibers, for use in a variety of applications such as apparel but also potentially lightweight auto parts and high-performance foams.[48] To that end, Spiber has partnered with Kijoma Industries since 2014, which is a subsidiary of Toyota, focusing on car interior materials including seat covers. By 2024, the share of Brewed Protein fibers could be increased in some collections. Japanese manufacturer Ueyama Textile began to use 35% Brewed Protein fibers in combination with 65% organic cotton, which constituted

[43] https://sourcingjournal.com/topics/raw-materials/pangaia-spiber-brewed-protein-microbes-amanda-parkes-349717/
[44] https://thebridge.jp/en/2021/01/spiber-jpy25b-funding
[45] https://www.carlyle.com/media-room/news-release-archive/carlyle-forms-strategic-partnership-new-generation-biomaterial; https://sourcingjournal.com/topics/raw-materials/spiber-biomaterials-brewed-protein-material-innovation-japan-carlyle-300109/.
[46] https://www.greenqueen.com.hk/japan-spiber-fiber-materials-microbial-fermentation-brewed-protein/
[47] https://thebridge.jp/en/2018/12/spiber-jpy5b-funding-for-mass-producion; https://spiber.inc/en/thailand/.
[48] https://spiber.inc/en/about/

a significant scale up compared to the previous 5% Brewed Protein to 95% cotton ratio used by Nihon Mempu.

In terms of partnership projects, Spiber launched a 'Biosphere circulation project' with Pagaia and Goldwin, which was later expanded to other brands including Kering, Eileen Fisher Inc, Johnstons of Elgin and DyStar.[49] The stated rationale for this project is that Spiber compiles the results from this testing of its materials to provide guidelines and standards for the circular design of products. It also aims to test how it can shift away from sugarcane and corn towards sugarcane bagasse or corn stover, or discarded textiles.

There is no information about its current tonnage, and thus it is difficult to know the scale of production that Spiber has and thus whether it can be seen as a success in terms of commercialization. From the available public data, it seems like Spiber's business strategy is to cater to high end and luxury markets, and not mass markets, and therefore does not large-scale production. Furthermore, there are questions about the degree of sustainability of the Brewed Protein fiber, as its feedstock comes from agricultural production and not agricultural waste and could be seen as competing with food production. But one of the important lessons from the Spiber case is the diversification of end-markets and the time it takes to create a commercializable fiber in terms of R&D.

2. Bolt Threads (biofabrication technology)

Bolt Threads was founded in 2009 by three scientists that combined expertise on bioengineering, biophysics and biochemistry. Initially, Bolt Threads sought to commercialize spider silk, which is extremely soft and strong, focusing on providing fibers for long-lasting, lightweight materials.[50] In 2017, it launched microsilk fiber as part of a Stella McCartney pilot collection.[51] However, the natural microsilk fiber was difficult to scale, so Bolt Threads shifted the end-market to the cosmetics industry in 2018, and used DNA sequencing of spider silk protein to create a derivative, which was put into yeast cells to create a bio-based polypeptide for skincare and cleansers that it calls 'b-silk'.[52] Bolt Threads initially sold b-silk under its own brand Eighteen B, but then switched to a model of selling its ingredients to other brands like Vegamour. It holds a total of 34 patents for b-silk (of a total 49 patents throughout the company) and has another 131 patents pending. B-silk could replace silicone elastomers in the cosmetics industry, which Bolt Threads estimates as a $4 billion market.

For the apparel industry, Bolt Threads shifted to developing mycelium for a customized alternative to leather called 'Mylo', which could be supplied for the footwear, handbags, and wallets product segments. While being based in California, in 2020 Bolt Thread announced that its mycelium production site would be in Arnheim, the Netherlands, given the ranking of

[49] https://worldbiomarketinsights.com/pangaia-goldwin-and-spiber-to-transform-agricultural-byproducts-into-biomaterials-for-fashion/; https://texfash.com/update/spibers-move-to-create-resource-base-for-designing-circular-products-gets-fillip-with-more-fashion-companies-joining-project.
[50] https://www.forbes.com/sites/amyfeldman/2023/10/04/biomaterials-firm-bolt-threads-formerly-a-unicorn-plans-spac-deal-at-a-250-million-valuation/
[51] https://boltthreads.com/about-us/
[52] Public interview with Bolt Threads CEO Dan Wiedmeier, October 2021 https://www.youtube.com/watch?v=yKilxLVV124

the Netherlands as the world's second largest exporter of mushrooms, making it a key global production hub.[53]

To bring its fiber products to market, Bolt formed strategic partnerships with a number of European tanneries, such as Heller Leder from Germany, to reduce capital expenditure and accelerate scale up. It also formed a partnership with a consortium of apparel buyers that consists of Adidas, Kering, Lululemon, and Stella McCartney. Lastly, Bolt engaged in a partnership with US-based Gingko Bioworks, as cell programming platform, to optimize the efficiency and quality of mycelium production as well as develop new proteins for biomaterials, fostering Bolt Threads envisioned image as a 'biotech platform'.[54]

In 2022, Mylo was launched for Lululemon and Stella McCartney products. Bolt Threads reportedly had raised $334 million from investors by 2023, including Baillie Gifford, Temasek, Top Tier, Founders Fund, Formation 8, Foundation Capital, and Golden Arrow Sponsor, LLC. However, in mid-2023 Bolt announced that it had to stop production of Mylo because it lacked the finance for scaling its mycelium production. Higher interest rates and the reallocation of venture capital funding to AI startups forced Bolt to turn to a public offering, but that also did not work although the reasons are not clear.[55] The CEO noted: 'Despite our intensive efforts, the current macroeconomic climate has made it increasingly difficult to secure the necessary capital to support the scale-up of emerging technologies'.[56] Thus, Bolt Thread has, for the time being, turned its attention back to b-silk, which the CEO emphasized 'can be made with third-party fermentation partners that are already at scale, versus Mylo, which requires a dedicated facility'.[57]

While the information is not always clear, it seems that Bolt Threads was successful with its b-silk (arachnid-free Microsilk) because that business model did not involve mass production. The process is patented and trademarked and seemingly the production is outsourced to third party manufacturers and then sold to cosmetic companies. Mylo was the first time that Bolt Threads moved into the sphere of production, and the step of large-scale production. This is underscored in the CEO's comment regarding the challenges of bringing technology to market: 'Problem No. 1 is making this stuff'.[58]

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[53] https://sourcingjournal.com/topics/raw-materials/bolt-threads-dan-widmaier-heller-leder-leather-tannery-mushroom-mylo-biomaterial-311257/; https://investinholland.com/news/bolt-threads-introduces-mylo-to-europe-from-the-netherlands/.
[54] https://vegconomist.de/fashion-und-beauty/lederalternativen/bolt-threads-ginkgo-bioworks/
[55] https://internationalleathermaker.com/mycelium-materials-company-bolt-threads-stops-production/; https://www.voguebusiness.com/sustainability/stella-mccartney-backed-leather-alternative-mylo-halts-production-bolt-threads-kering-ganni-adidas-lululemon#:~:text=US%20startup%20Bolt%20Threads%20has,Dan%20Widmaier%20tells%20Vogue%20Business. https://www.yahoo.com/lifestyle/bolt-threads-goes-public-ceo-202840770.html?guccounter=1&guce_referrer=aHR0cHM6Ly93d3cuZ29vZ2xlLmRlLw&guce_referrer_sig=AQAAAEiJA7faF1dIqwjBAmlYAIUy8O_GXnV4aX0WQZFx72pbd6mSdI_zKfyIC7Z9iMVsB2es-aIAsztZ3VuNqkJ9js76BjxXLcAKVgdsAill7mXy2bx1X8HCACV9zsgKCQpvYORTOF9OHe0Xwy6mlAXv4ZYQoKpbTHb_ag5FbMynMfKV.
[56] https://sourcingjournal.com/sustainability/sustainability-materials/bolt-threads-ceo-dan-widmaier-spac-merger-ipo-biomaterials-b-silk-mylo-459903/.
[57] Ibid.
[58] Ibid.

3. **MycoWorks (biofabrication technology)**

MycoWorks was initiated in 2013 by a group of artists that had worked with mycelium as an art material, but it did not become a green fiber tech company until it received support in 2016 from the accelerator program by Indiebio.[59] At that time it also patented its mycelium growing process and produced the first 'fine mycelium' prototype products, using the early stage funds that it received from Indiebio. The initial product yielded high standard results in terms of durability and softness but lacked sufficient strength. By 2017, MycoWorks was unable to secure further funding steps, so it hired its current CEO Matt Scullin who had a background in materials science. Scullin sought to shift the narrative vis-à-vis investors away from the focus on a unique quality product towards building up a bio-materials platform that caters to many different end-markets such as food, construction, medicine as well as apparel. The vision sold to investors is that MycoWorks uses mycelium not as a single product to be harvested but rather a novel class of materials, with MycoWorks at the forefront of managing and defining tunability processes, defining standards for testing and in process measuring, and ultimately creating new properties of the cell structures (i.e. with cells further apart for foam, and denser for bricks).[60]

By 2019, it established its first garage-size pilot plant in Emeryville, California, for which it pursued its first major round of fundraising. It received 62 million USD in 2020 and 125 million USD in 2022 to finance the first factory at scale, raising in total around 350 million USD.[61] As part of its commercialization strategy, MycoWorks aims to bring mycelium to the apparel market through own fabrication, rather than licensing its tech. The current key product is called 'Reishi', which is grown in California but then tanned and finished by tannery partners in Europe, which use Mycowork's proprietary chrome free tanning and dyeing procedure.[62] Reishi is built on Mycowork's proprietary growing process that allows for a strong three-dimensional structure of 'Fine mycelium' that can be customized, targeting the high price luxury leather market.[63]

In 2023, MycoWorks claimed to have reached breakthroughs in mycelium fermentation and tanning as well as in flexibility, finish adhesion, tear strength and abrasion resistance—which were necessary to meet the high performance standard of the luxury sector.[64] It opened a new facility in South Carolina, which is the largest mycelium production facility in the world and will employ initially 150 workers drawing on engineers from consumer goods, automotive, food, pharmaceutical, and biotechnology industries who have adapted robotic equipment and

[59] Public interview with MycoWorks co-founder Sophia Wang, and current CEO Matt Scullin, May 2022: https://podcasts.apple.com/us/podcast/talk-01-unfiltered-origin-stories-with-matt-scullin/id1613225602?i=1000563418918.
[60] https://patents.google.com/patent/US20120135504A1/en; Public interview with MycoWorks CEO Matt Scullin, June 2023 https://podcasts.apple.com/us/podcast/talk-14-why-mycelium-with-ceo-matt-scullin/id1613225602?i=1000616108753.
[61] https://sourcingjournal.com/topics/raw-materials/mycoworks-mycelium-leather-reishi-125-million-investment-south-carolina-factory-323050/
[62] https://icff.com/stories/a-biomaterial-that-challenges-leather/
[63] https://www.mycoworks.com/fine-mycelium-an-advanced-materials-platform
[64] https://sourcingjournal.com/topics/raw-materials/mycoworks-mycelium-leather-reishi-nick-fouquet-hats-luxury-cuir-du-vaudreuil-446358/

systems to handle the unique tray-based biomaterials process. The factory is run by engineers that bring experience in scaling biotech and food manufacturing.[65]

MycoWorks partners with a number of large brands, including Hermès (i.e. for leather for Hermès, Sylvania leather bags), General Motors (luxury EVs), Ligne Roset, Heron Preston and Nick Fouquet. Importantly, it employed the former Hermes CEO Patrick Thomas at its board, 'helping to meet the quality standards' of Hermes.[66] Thus, the commercialization strategy of MycoWorks targets the luxury sector, which requires a much smaller volume of production than mass consumer markets and allows the company to scale slowly. It is not yet clear why MycoWorks has performed better than Bolt Threads in commercializing mycelium leather, given that they raised a similar amount of initial financing and had similar revenue structures, but its buyers are luxury and thus have higher prices and smaller volumes than even the higher end markets targeted by Bolt Threads. It seems that MycoWorks has a better manufacturing team, but also more expensive equipment. These factors will be followed up in interviews.

4. Renewcell, now Circulose (regenerative cellulose)

Renewcell was founded in 2012 by two professors in chemistry from the Swedish Royal Institute of Technology. Prior to Renewcell, they had worked on projects on commercial pulp dissolvement technology. Renewcell's technology creates cellulose by chemically recycling cotton-rich textile waste. According to a former employee, the technology is not novel, but rather the idea to commercialize this process. The founders aimed to tap into a 'cellulosic gap', which they anticipated would become a key raw material for construction, plastic and other types of materials. Renewcell developed a recycling process to prepare waste garments for processing (including de-button, de-zipp, etc) and then use water based chemical process to remove dyes and other contaminants the textile waste and then separate cotton, crush the remains into a pulp/slurry and give it correct properties so that it can be made into rayon/viscose fiber. The dried slurry is then used to create sheets of "pure Circulose" – the sheets are packaged into bales that are then sent to fibre producers – which then use this as an input for viscose, lyocell, modal, acetate other types of regenerative cellulosic fibers.[67] The objective of the company was to fill the 'cellulosic gap': that there would be a high demand for cellulose in the future as it is used to substitute other materials and tha alternative feedstock was required: stop using trees and use waste instead. The technology was not new, but they devised a way of treating a new feedstock with which to make cellulose.

Lab trials involved producing pulp in a lab and shipping to an institute to produce a few lyocell fibers, which were knitted into sample dresses in 2014.[68] After lab trials and registering the patent, the company decided to scale up, building a demonstration plant in 2018 that was about 2000 square meters, staring with 2000-3000 tons per year. The demonstration plant is used to learn and to raise capital.

[65] https://sourcingjournal.com/sustainability/sustainability-materials/mycoworks-mycelium-south-carolina-factory-gozen-balenciaga-lunaform-3-3-million-seed-raise-462941/; https://www.innovationintextiles.com/mycoworks-opens-first-commercial-plant-in-south-carolina/.
[66] Public interview with MycoWorks CEO Matt Scullin, June 2023 https://podcasts.apple.com/us/podcast/talk-14-why-mycelium-with-ceo-matt-scullin/id1613225602?i=1000616108753
[67] Interview with former Renewcell representative, January 2023.
[68] Ibid.

In 2017, Renewcell received a 10% equity investment by H&M's investment arm Co:lab. According to a former Renewcell employee, the H&M investment was meant to crowd in other equity investors and creditors, showing that a large fashion brand and future buyer took interest and Renewcell passed their due diligence. Renewcell also signed an offtake agreement with H&M to take the fiber, signaling that there will be market demand. In 2018, the first industrial demonstration plant was built in Kristinehman, Sweden, which produced 2000-3000 tons annually and was later scaled to 7000 tons. In 2020, Renewcell pursued an IPO on the Nasdaq Nordic and raised a EUR 30.75 million export credit by the European Investment Bank to buy machinery. According to the Capital IQ database, Renewcell was able to raise significant funds from share issuance. Its 2020 IPO yielded USD 103 million, and it obtained another USD 49 million and USD 41 million through secondary issuances in 2022 and 2023 respectively.

Renewcell opened its first large scale production plant by moving into an existing pulp mill in Sundsvall, northern Sweden, which had an initial capacity of 60,000 tons and potentially could produce 120,000 tons of pulp annually. Moving into a 'brownfield' site allowed Renewcell to reuse buildings, infrastructure (processing equipment and chemical tanks), utilities and wastewater management, and the existing workforce. The location in Sweden also offered low cost of hydropower, proximity to the headquarter for continued R&D in the production process, and EU trade regulations for the feedstock that were transparent and came with low or no tariffs. According to the management, the latter stood in contrast to regulations in alterative locations in South Asia that had import bans or high tariffs on feedstock.

Pursuing the most ambitious scaling project at the time was motivated by the ambition to rapidly bring down the cost curve. The aim was to become cost competitive with existing wood pulp factories, which according to a former Renewcell representative were still 5-6 times larger even with the new capacity of Renewcell. As a potential long-term cost advantage vis-a-vis these existing pulp producers, Renewcell was banking on lower feedstock costs once its textile waste recycling network was in place. Its strategy revolved around creating regional production bases with regional feedstocks of textile waste by 2030, including one in North America to tap into post-consumer textile waste from the North and Central American market, and one in South Asia, using post-production textile waste.

Renewcell only produced the pulp not the fiber. Engaging in fiber production was rejected as it would have quadrupled the investment volume.[69] Therefore, it sold its pulp to fiber producers, incumbent firms that already produced viscose and lyocell fibers from wood pulp. Renewcell major customers were Lenzing (Austria, but most of production capacity China and Indonesia, now also plant in Thailand), Birla (India), Sateriand Tangshan Sanyou (both in China). In addition, Renewcell tried to initiate a network of more than 100 fiber producers and mills that expressed interest to source Circulose. Brands also played an important role in signaling market creation, and by early 2023, Renewcell was 'talking with 50-60 brands, including PVH, Levis and Inditex on fast fashion, as well as smaller high end brands such as Gianni, Filipa K, Jade Cooper'.[70]

[69] Interview with former Renewcell representative, January 2023.
[70] Ibid.

However, it became clear that sales were massively underperforming in the summer of 2023. In an interview in November 2023, the CEO at the time admitted that most of the output that was sold in 2023 came from the pilot plant, instead of the new commercial plant in Sundsvall. Circulose was still at a 35% premium, and several buyers did not honor their offtake agreements. However, Renewcell did not want to take legal action, rather hoping that the offtake agreements of firms such as H&M, which had not purchased the 2000 tons based on the contract, would eventually be honored.[71] This underscores the precarious bargaining situation in which Renewcell was vis-à-vis its buyers. By autumn 2023, orders began to decline rapidly, and despite a short-term credit from H&M, Renewcell declared bankruptcy in February 2024 based on shortage of funding of its operations.

There has been much speculation about the causes of Renewcell's bankruptcy.[72] Here we give our analysis based on reviewing the publicly available material as well as interviews with industry actors. Although Renewcell generated a lot of interest among major fashion brands, most of these contacts did not result in large scale and long-term offtake agreements that were honored. This in turn is linked to the fact that Circulose was selling at a price higher than conventional wood pulp.[73] In addition to the price premium issue, other analysts questioned the speed at which Renewcell sought to scale, compared with buyers' more cautious approach to switching all of their man-made cellulosic material to regenerative cellulose given uncertainties around how this new type of cellulosic fiber would perform in yarn spinning and onwards down the supply chain. Fiber producers and textile mills needed to adapt their processes to integrate the sheets of Circulose pulp into fiber and fabric, and many fashion brands did not budget a premium on Circulose. Given that viscose/lyocell only constituted 6% of the global fiber market at the time, it would mean buyers switching most of their supply from conventional cellulosic fiber to this new regenerative cellulosic fiber. Buyers were very hesitant to do so at that scale and pace.[74] Thus, Renewcell's position at the very upstream end of the supply chain meant that it did not control the supply chain and had to rely on a number of actors including fiber producers, textile mills and brands.

After its bankruptcy, Renewcell's intellectual property and the Sundsvall plant were acquired by Swedish private equity firm Altor, which renamed the company Circulose.[75] Notably, Altor is owned by Vargas, which is the major investor in Syre, the only polyester textile recycling firm in Europe, in which H&M also has a major stake (see below).

The case of Renewcell shows that the challenge of commercializing green fiber technologies is not only about reaching scale. It suffered from reaching scale too quickly in the context where market demand for regenerative cellulosic fiber was not keeping pace and where the time frame for testing new fibers through the apparel global supply chains of buyers was estimated at over a year. Without compulsions otherwise, apparel buyers were hesitant to commit. The other key takeaway is that this startup's dependence of going public to finance

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[71] Public interview with Magnus Hakansson, CEO of Renewcell, November 2023 https://www.ecotextile.com/2023112231427/materials-production-news/podcast-exclusive-interview-with- renewcell-ceo.html

[72] https://www.forbes.com/sites/brookerobertsislam/2024/02/27/what-we-can-learn-from-renewcells-financial-struggles/?sh=769b1b5a2bb7

[73]Greenbiz claimed that Circulose had twice the price of conventional visoce fibers. https://www.greenbiz.com/article/why-renewcell-failed;

[74] Interview with a staff member of a fiber company that worked closely with Renewcell.

[75] https://altor.com/altor-takes-first-step-to-build-global-champion-for-renewable-cotton

its commercialization meant that it was at the mercy of stakeholders that wanted fast returns on their investment. Notably, Renewcell has been bought by an investment firm that can be characterized as more patient capital and with a clear green agenda.

5. Spinnova (regenerative cellulose)

Spinnova is a Finnish startup established in 2015 by cellulose and biomaterial researchers from the Technical Research Centre of Finland (VTT), which patented their technology in 2014. VTT is a public research institute. In the early 2000s, there was a big collapse of demand in the forestry industry in Finland, as was the case in other countries. The utilization rate for fiber and paper plants in Finland declined significantly, and thus the government wanted to develop something new.[76] VTT researchers took up technology research in areas related to this pressing economic issue.

Spinnova's technology primarily uses wood pulp, which is derived from sustainably sourced wood and other cellulose-rich materials like agricultural waste and recycled cotton textiles. It involves milling down the wood pulp or cellulose-rich waste into extremely fine fibers which are then suspended in water to create a paste; its technology does not break down the cellulose chemically but rather is a mechanical modification. The paste is then extruded in a way that aligns the cellulose fibers, allowing them to bond together naturally, forming a strong and cohesive filament. The fiber is then dry spun, collected and post-processed, ready for spinning into yarn. Spinnova fibers are blended with other preferred fibers and can be integrated into innovative and conventional textile processing methods, like the processing of cotton. The result is a material that imitates cotton. Spinnova claims that its fibers can be infinitely recyclable, but some industry observers are less optimistic. They note that man-made cellulosic fibers cannot survive too many recycling cycles, as the fiber degrades.[77]

In 2017, Spinnova received an investment from Brazilian cellulose company Fibria, which acquired 18% of Spinnova's total capital for a total amount of €5 million. The following year, Spinnova secured a €4.5 million loan from OP Bank, guaranteed by the European Investment Bank, along with an additional €3 million from Business Finland, a public sector agency.[78] With this financing, Spinnova built a pilot mill by the end of 2018, which drew interest from several well-known brands, some of which began collaborating on R&D. In 2019, Spinnova raised €11 million in funding from existing investors, including family investment offices, private investors, a VC investment fund, and industry partners.[79] With this financing, it produced its first demo products and finalized production processes and product properties.

In June 2021, Spinnova went public on the Helsinki Nasdaq with the primary objective of financing scaling efforts, raising €100 million, which was used to finance a pilot plant that could produce 1000 tons per year. The pilot plant was a joint venture with Suzano, the largest wood-pulp producer and which provided the raw material. That plant opened in Finland in 2023.

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[76] Interview with a former staff member of Spinnova, which was also a spin-off of VTT.
[77] Interview with fiber development specialist at the Research Institutes of Sweden, September 2024.
[78] https://www.just-style.com/news/spinnova-secures-funding-to-accelerate-pilot-factory/?cf-view.
[79] https://spinnova.com/news/press-releases/spinnovas-technology-for-sustainable-textile-fibres-gets-11-meur-investment-for-commercial-scaling/

However, there is no indication that Spinnova tried to develop feedstock from cotton textile waste or agricultural waste. It was working with Renewcell to use its technology to create fiber from cotton textile waste without chemicals, with the aim of producing consumer products by the end of 2024.[80] But then Renewcell went bankrupt, and Spinnova's capitalization fell.

To avoid the same destiny as Renewcell, Spinnova revised its business strategy in 2024 to focus on selling the technology itself instead of only producing fibers. This business model shift occurred because there were not enough buyers, the economic conditions were unfavorable, and the previous example of Renewcell gave a clear lesson to the similar situation in which Spinnova was finding itself.

6. Infinited (regenerative cellulose)

Infinited is also a Finnish firm that spun off from the Technical Research Centre of Finland in 2016.[81] It has pursued a different business strategy than Renewcell and Spinnova. Its business strategy was to obtain both equity investments and offtake agreements from a wide range of global buyers, and to a smaller extent apparel suppliers, so as to secure mid-term demand and investors' interest but scale with caution, to avoid creating both supply bottlenecks and excess capacities in the scaling process. In short, Infinited sought to reduce risks of overcapacity by securing demand before investing in large-scale production.

Within the meta-technology of regenerative cellulosic, the specific technology used by Infinited is different from Renewcell and Spinnova. It uses carbamation technology, which breaks down the cellulose to the molecular level, activates it with urea, and then dissolves it to create liquid cellulose, which is then wetspun into new fiber filament. Infinna is biodegradable of the same quality as traditional fibers and is recyclable.[82] Infinited uses pre- and post-consumer textile waste that contains at least 88% cotton, and it claims that its fiber is a good substitute for virgin cotton. The first pilot plant was constructed in 2018.

Its first commercial scale factory in Finland for 30,000 tons is expected to begin only by 2026, but by 2024 it had received USD 43 million in investment from a range of corporate venture capital arms of large buyers including Inditex, Fast Retailing, Bestseller, Zalando, and Goldwin as well as apparel manufacturers such as the Korean firm Youngone. It secured off-taker agreements with H&M, Inditex, Patagonia, Bestseller, Pangaia, and PVH, selling out its prospective production capacity for several years.[83]

This spring 2024 capital injection came at a time when Renewcell went bankrupt. Industry analysts have sought to explain the different trajectories of the two firms based on three factors. First, Infinited managed a better way to secure feedstock, obtaining post-consumer textile waste from Europe-based garment collectors and sorters. The 88% minimum cotton

[80] http://luxresearchinc.com/wp-content/uploads/2023/09/spinnova-renewcell-are-teaming-up-to-fuel-fashions-circular-future-%E2%80%93-sourcing-journal.pdf.
[81] VTT began encouraging such spin offs by 2005. See https://www.vttresearch.com/en/about-us/invest-innovation.
[82] https://sourcingjournal.com/sustainability/sustainability-news/zara-uniqlo-hm-invest-40-million-sustainability-498734/; https://infinitedfiber.com/our-technology/.
[83] https://infinitedfiber.com/blog/2023/10/27/infinited-fibers-flagship-factory-progresses/; https://sourcingjournal.com/topics/raw-materials/infinited-fiber-company-russia-ukraine-war-chemical-costs-200-percent-381740/

content is a much lower threshold than the 95% threshold of Renewcell. Second, securing advanced offtake agreements was easier for its Infinna fiber was easier compared to Renewcell's Circulose, given that Infinited produces fibers ready for spinning provided an easier integration into existing supply chains and thus it can also circumvent the collaboration with fiber producers that Renewcell needed to undertake. Third, Infinited marketed its Infinna fiber as a cotton replacement, thus targeting a potential 22% of global fiber sales, or 25.5m ton market.

Currently, the company has two pilot facilities in Finland. The construction of the new commercial scale facility (within a decomissioned pulp and paper plant in Finland) is expected to cost 400 million euros ($437m), which Infinited has not yet secured, and aims to raise throughout 2024.[84] Thus, it remains to be seen whether Infinited will succeed where Renewcell and Spinnova did not. If it is successful, the owners of Infinited eventually plan to take the business model as a turnkey solution where the recycling and wet spinning processes are sold under a license model.[85] As its CEO stated "Licensing is a long term play that needs further maturity of the technology; decreasing the risk [of this new technology] is needed first" to make licensing appealing for adopters to go 'all in'.

7. HeiQ AeoniQ™ (AeoniQ, for short) (regenerative cellulose)

AeoniQ is a subsidiary of Swiss based firm HeiQ, which was founded in 2005 as spin-off from ETH Zurich University. HeiQ operates as a material firm with four business segments, including coating and polymers, probiotics, finished goods, and performance textiles. In its performance textile division, HeiQ introduced a number of new technologies that apparel brands and retailers use, including technologies on odor control, catalytic air sanitizing textile, and thermal regulatory textiles.[86] The idea for AeoniQ was born out of the efforts of HeiQ to develop a technology that prevents microfiber abrasion for outerwear fleece, for a particular customer. However, it was difficult fully reduce microfiber abrasion, so HeiQ decided to focus on the development of a biodegradable polymer within AeoniQ, a subsidiary founded in 2021.

AeoniQ produces what it would call a new generation of man-made cellulosic fiber, because it is a filament (long continuous fibers) like polyester but made out of cellulosic material. Thus, AeoniQ technology creates filament cellulose yarn that achieves the high tenacity and elongation with no fibrillation that makes polyester unique, and such as used fiber. In contrast, cellulosic fibers such as lyocell have high tenacity and elongation but also fibrillation, which makes it less durable. But AeoniQ cellulosic filament, unlike polyester, is biodegradable in a landfill within a cycle of three months.[87] AeoniQ's technology is based on the kind of solvent

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[84] https://www.forbes.com/sites/brookerobertsislam/2024/03/12/how-infinited-fiber-raised-43m-amidst-textile-recycling-uncertainty/#:~:text=How%20Infinited%20Fiber%20Raised%20%2443m%20Amidst%20Textile%20Recycling%20Uncertainty,-Brooke%20Roberts%2DIslam&text=Senior%20Contributor&text=Just%20weeks%20after%20fashion%27s%20leading,million%20euros%20(%2443.7m).

[85] Public interview with Infinited founder and CEO Petri Alva, April 2021. https://fashionmade.libsyn.com/regenerating-textiles-with-infinited-fiber

[86] https://www.heiq.com/

[87] Public Interview with CEO of HeiQ, January 2023 https://www.linkedin.com/posts/heiq-aeoniq_circularfashion-fashion-sustainablefashion-activity-7018590024111669248-bAOX?utm_source=share&utm_medium=member_desktop

used and the production process. The raw material includes bacterial cellulose produced from agricultural waste in HeiQ's fermentation reactors, and regenerative cellulosic pulp from recycled cotton textiles sourced from other firms.[88]

AeoniQ's pilot plant in Austria, established in 2022, used wood pulp cellulosic raw material for testing the technology. In its 1,700 ton 'blueprint' factory that it is building in Porto, Portugal, it plans to use regenerative cellulosic pulp from recycled textile waste. It is currently working with suppliers such as Circulose, Circ and Sodra, which are in their own processes of scaling up and improving their technology at scale, to deliver the volume and quality of regenerative cellulosic pulp that AeoniQ needs. AeoniQ was sure that that raw material would be there by 2026.[89]

AeoniQ's technology has no problem mixing feedstocks, but mixing poses other problems, so for now it only plans to use cellulosic pulp from textile waste. First, apparel brands and retailers are more interested in sourcing fibers from recycled textile, as they can tell a better story, and they can continue to encourage consumers to buy more of their products, promising that they can be recycled. Furthermore, given EU regulations related to the digital passport and traceability, mixing feedstocks can create problems for the certificate of origin. Lastly, it is taking more time to arrange a supply chain of firms to deliver agricultural waste, as it has a perishable quality.

The blueprint factory is a middle step, before building a mega factory with a 30,000 tons capacity, which is envisioned to be completed by 2028 and with AeoniQ being able to produce 200,000 tons of its regenerative cellulosic filament yarn by 2030. It is likely that this factory will be located in North Africa or Asia, depending on the creation of partnerships. Scaling up quickly is important, but it requires building expertise and finance. AeoniQ hired experts in factory production and temporarily used consultant companies and engineering companies.

The small blueprint factory, costing around 250 million USD, was financed through a mix of equity, loan and grants (from the Portuguese government), but the bulk came from equity, from HeiQ and from venture capital investors interested in green technologies. Investors from the apparel industry have been few and much smaller, with Hugo Boss, Lycra and MAS taking small equity stakes.[90] Apparel brands have not come with bankable offtake agreements and generally do not want to finance the green tech even though they want to benefit from it.

The role of MAS is much bigger than investment; it is a partnership to develop the cellulosic filament yarn production through further R&D in the production process and its use to produce fabric. MAS has textile production experience with polyester fabrics that it produces

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[88] https://sourcingjournal.com/sustainability/sustainability-materials/mas-holdings-investment-heiq-aeoniq-cellulose-yarn-polyester-circulose-sustainable-444710/

[89] The information on the remainder of this sub section was obtained during an extensive interview with AeoniQ's director business development, September 2024. Other sources of information are marked with an additional footnote.

[90] https://www.heiq.com/news/heiq-aeoniq-game-changing-decarbonizing-yarn-endorsed-by-hugo-boss-and-the-lycra-company/ https://group.hugoboss.com/en/responsibility/news-and-downloads/latest-topics/message/hugo-boss-invests-in-a-sustainable-apparel-technology; https://www.innovationintextiles.com/boss-and-lycra-invest-in-heiq-aeoniq-yarns/ https://www.forbes.com/sites/brookerobertsislam/2023/07/05/mas-holdings-and-heiq-take-sustainable-plant-polyester-mass-market/?sh=2d0436df12cb

and assembles into garments for the top performance wear brands. Thus, it can help making sure that the filament yarn is produced to the specifications of buyers, and also help convince brands to adopt this new yarn in their products. MAS agreed to procure 3000 tons of AeoniQ yarn until 2025, and an additional 5000 tons per year between 2026 and 2029.[91]

According to their strategy, AeoniQ expects its regenerative cellulosic filament yarn price at the Porto factory to be lower than lyocell and Cupro, and thus a replacement for those 'brown' fibers. However, its strategy relies not only on the apparel industry. It also targets its regenerative cellulosic filament yarn to other end markets, including home textiles, the automotive industry, and technical applications. Having multiple end markets provides the demand that it needs to scale. Its plan is to start with small volumes and introduce initially with blended fibers (its own and virgin sources) to reduce costs. As demand grows and production volumes increase, the price will eventually fall to be comparable to virgin polyester by 2030. However, AeoniQ was also fairly confident that EU regulations would eventually tax virgin polyester and thus increase its price. But that remains to be seen.

The case of AeoniQ provides three major insights in commercializing green fiber technologies. Because AeoniQ produces a filament yarn, it is at a later stage in the supply chain: it buys the regenerative cellulosic pulp of the companies considered above as a feedstock. With the yarn that goes directly into textile fabric production, it can establish direct partnerships with high capability fabric and garment manufacturers such as MAS. Second, offering a type of man-made cellulosic filament yarn that can replace various fiber categories provides potentially more buyers, although it will take time for buyers to realize that it is not cotton or polyester, but a new kind of fiber. AeoniQ can be a 'drop in' solution for their existing polyester fiber portfolio, but it could also be much more. Third, given financing challenges of startups with uncertain markets, building a 'blueprint' factory with smaller tonnages might be a more viable option than moving straight from small pilot plants to large scale mega factories.

8. Ambercycle (polyester textile to textile recycling)

Ambercycle was founded in 2015 in the US and introduced its 'Cycora' fiber technology in 2021 and plans to build its first commercial plant in 2025. Cycora technology was developed by two chemistry students from the University of California, Davis, which can synthesize out the polyester part of blended textiles.[92] It is not patented, but rather the process is a trade secret. To scale the technological process, Ambercycle engages in technological development in-house, drawing on consultants or hiring experts that have experience working, for example, in oil companies. Green fiber tech firms have to develop capabilities in large-scale manufacturing. Scaling is not about doubling the process, but rather changing the parameters and thus involves extensive R&D in the scaling process. This is true for all green fiber tech firms.

[91] This point is made based on research carried out by the authors on Sri Lankan transnational apparel suppliers (see Maile and Whitfield, forthcoming b).
[92] Interview with former Ambercycle employee, August 2024.

Ambercycle received more than 100 million USD venture capital, including from Inditex, Bestseller, H&M, and Far Eastern Group.[93] However, these equity investments alone are not sufficient to create a business case. In addition, Ambercycle signed offtake agreements with Inditex (worth USD 70 million from 2025 onwards), Bestseller, and athleisure firm Athleta (GAP Inc.).[94] However, firm press releases of offtake agreements have to be put in perspective that they are small compared to what a large-scale plant will produce.

Ambercycle has received interest from a range of integrated synthetic fiber-textile producers, which resulted in partnerships with Shinkong synthetics from Taiwan and Hyosung from Korea.[95] Through these partnerships with fiber-textile firms, Ambercycle can de-risk its scale up by leveraging established production capacity in Asia for high quality yarn, and existing buyer networks with sportswear brands. Finally, Ambercycle partners with MAS, which signed a three-year offtake agreement (2025-28, for roughly 10 million garments).[96]

The main challenge is the cost to build a factory, and the cost of building it together with the financing costs make the Ambercycle's production costs high and thus its unit price too high for buyers compared to virgin polyester. One industry expert noted that the standard price for polyester yarn is 1-2 USD per kilogram, while recycled polyester yarn is currently about 15 USD per kilogram. Thus, apparel brands and retailers are hesitant to sign offtake agreements because they would not hit their margins.

Furthermore, there are challenges with establishing the textile recycling infrastructure that is required for firms like Ambercycle to use post-consumer waste. At the moment, Ambercycle is only using post-production (pre-consumer) waste. There is also the cost of creating the supply chain for textile waste, whether it is pre or post-consumer, which increases the firm's total costs, at least initially.

9. Circ (polyester textile to textile recycling)

Circ is based in Virginia, USA. It started as a biofuel start-up in 2011, receiving grants from the Virginia Tobacco Region Revitalization Commission to use tobacco as a biofuel. However, soon after its launch, it shifted to focus on recycling blended poly cotton.[97] In 2023, it operated a pilot factory in Virginia and announced the goal to open a large-scale factory with more than 50,000 tons annual capacity by 2025.[98]

Circ's polyester textile-to-textile recycling technology draws on a hydrothermal reaction process that allows it to use blended textiles as inputs, but also processes both cotton and

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[93] https://www.ambercycle.com/news/ambercycle-raises-21-6-million-to-build-circularity-ecosystem-in-the-fashion-industry

[94] https://sourcingjournal.com/sustainability/sustainability-news/gap-ambercycles-regenerated-polyester-athleta-cycora-circularity-zara-saucony-tombogo-498180/

[95] https://sourcingjournal.com/sustainability/sustainability-materials/ambercycle-hyosung-partnership-cycora-creora-recycled-textiles-514465/; https://sourcingjournal.com/topics/raw-materials/ambercycle-regenerated-polyester-textile-recycling-shinkong-synthetics-438677/.

[96] https://sourcingjournal.com/sustainability/sustainability-materials/ambercycle-partners-with-mas-holdings-to-scale-cycora-regenerated-polyester-circularity-513873/

[97] Apparently, a Swedish commodity trader asked whether the firm could also recycle textile. See https://www.bloomberg.com/news/articles/2021-06-01/fashion-s-waste-problem-inspires-textile-recycling-tech-breakthrough

[98] https://carboncredits.com/revolutionizing-textile-recycling-and-curbing-fashion-emissions-with-htc/

polyester fibers for reuse. (Notably, some recycling fiber tech firms can process blended textile waste, but then only use the cotton, or the polyester, part.) Circ uses subcritical water (water kept under pressure so it can be heated beyond the boiling point) and combines this with a chemical catalyst such as sodium hydroxide (lye) to break the bonds of the polycotton blended fabric, which according to Circ uses less chemicals. Based on this, Circ can recover cellulose pulp for lyocell, while the liquid polyester that is generated can be converted to polyethylene terephthalate chips that are the basis for polyester.[99]

Circ attracted a range of investors. As part of the Series A and B funding rounds until mid-2022, Circ generated USD 38 million, collecting investments from Inditex, Breakthorugh Energy (Bill Gates Foundation), and Patagonia. A Series C financing round in March 2023 generated 25 million USD from Zalando, Avery Dennsion (digital labels) and Youngone Corp.[100]

In terms of commercialization, Circ pursues two routes. The first one is to build a partnership network with a small number of textile producers, which Circ markets as a 'Circ ready community'.[101] This network consists of firms that underwent a certification/testing process to replace virgin inputs with Circ. It includes firms such as AGI Denim (garment manufacturer Pakistan), Foshan Chicley (textile producer, China) MAS Holdings, Giotex, Marubeni Corporation (industrial textile, Japan), Pyratex, Selenis, Soorty, Tainan Spinning Co., Shinjintex, and the Taiwan Textile Research Institute. These firms will receive technical support services from Circ throughout the integration process.[102] Circ is being more proactive than the other firm cases in building its supply chain, but also selective in its network.

In mid-2023, Circ signed a partnership agreement with Taiwanese yarn manufacturer Acegreen for the offtake of recycled cellulose.[103] Additionally in mid-2024, Circ announced a partnership with Taiwanese Far Eastern Group, a large scale 23 billion chemical fiber and textile producer, which invested equity in Circ. The center of Circ's partnership with Far Eastern Group contains an agreement that Circ can tap into the large-scale production capacities of Far Eastern across Asia. Far Eastern aims to integrate the recovered monomers into its existing production infrastructure, which provides Circ with access to key buyers that Far Eastern caters. According to Circ's CEO, Far Eastern agreed to take the monomers at initially lower volumes, in contrast to most other chemical fiber firms which required initial take off that would have exceeded Circ's current capacity.

These partnerships with yarn and textile producers in Asia allow Circ to become a plug and play solution, as its CEO put it: 'Like many material innovators (….) friction is the enemy of

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[99] https://cardinalnews.org/2024/03/26/a-circular-fashion-company-is-making-danvilles-old-history-with-textiles-new-again/; https://circ.earth/our-technology/; https://techcrunch.com/2022/07/12/pivoting-from-tobacco-waste-to-textiles-circ-puts-a-fresh-spin-on-clothing-recycling/?guccounter=1&guce_referrer=aHR0cHM6Ly93d3cuZ29vZ2xlLmRlLw&guce_referrer_sig=AQAAALaNnPS1UGgHzXR6yPyNnTW7LiACSOfF4ob4pgQiEPA2EeRSr2kFq6qmvYRB1FXKqJnfC00hmejSVKWr2q8Lb4g53EsJr77XI4VJCtR1qfLh7BYJJj_yT7whdlfUOkclhOVMP9UAdjt38Q4JC-pBNJUcE5oPHSpJMpim25PMERkb.

[100] https://www.businessoffashion.com/news/sustainability/textile-to-textile-recycling-company-circ-closes-25-million-investment/

[101] https://sourcingjournal.com/sustainability/sustainability-materials/material-world-innovation-biomaterials-amsilk-billabong-circ-sway-seaweed-recycled-polyester-515900/

[102] https://circ.earth/circ-ready/

[103] https://circ.earth/circ-and-acegreen-partner-to-manufacture-fiber-from-reclaimed-polycotton/

adoption, and brands are looking for a drop-in solution that doesn't require them to rebuild the wheel, or chain, so to speak'. [104] What is unclear, as interviews with Circ have not been conducted yet, are its sources for feedstock and thus its textile waste infrastructure, but it seems that sourcing blended textile waste is not an issue at this stage. Being able to use blended textile waste gives Circ more flexibility with feedstock, and producing both recycled cotton and polyester fiber products gives its business model greater profitability.

10. Syre (polyester textile to textile recycling)

Syre was founded in 2023 in Sweden. It is a collaboration between H&M, a top ten global apparel buyer, that comes in with an offtake agreement and Vargas, an impact investor that has demonstrated its experience in scaling new green technologies across a range of industries, bringing the organizational capabilities required to scale production. The main motivation came from H&M, which saw that there was no European firm trying to scale polyester textile to textile recycling technologies.[105] H&M approached Vargas, which had a track record of scaling green technologies and was a Swedish company. Vargas is a specialist in scaling industrial solutions. The founder of Vargas, Harald Mix, had a private equity firm (Altor) first and then established Vargas to specialize as something between a private equity firm and an infrastructure fund. Vargas successfully scaled Northvolt (lithium-ion batteries for electric vehicle batteries), H2 Green Steel (carbon neutral steel), and a heat pump and energy storage company. Its key strategy was to negotiate offtake agreements with end users.[106]

Vargas provided the bulk of the investment, together with TPG Capital and other impact investors, totaling around 100 million USD. H&M signed an off-taker agreement with Syre over seven years valued at 600 million USD off-taker agreement over 7 years. Some sources not that this agreement could cover 50% of H&M's demand for recycled polyester.[107] The financing of Syre can be considered project financing ('patient capital'), not financing with short term margins.

Vargas bought the technology from a small firm in North Carolina called Premier Plastics, which has the patent for a glycolysis technology that uses the solvent found in automotive coolant to break down polyester into its constituent molecules, which is followed by repolymerization and spinning. Most of the people hired in Syre come from large firms such as Volvo and Polestar, with experience in scaling a company.

The first commercial plant was located in a textile cluster in North Carolina, which is close to its R&D center and where it can collaborate with other firms that can potentially provide recycled textile fibers such as Unifi and Circ. It is just one production line, where it can solve production issues and create a blueprint factory. Once that is done, it plans to scale very quickly, creating a large-scale factory in Southern Europe and Vietnam by 2027, which gives it

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[104] https://sourcingjournal.com/sustainability/sustainability-materials/textile-to-textile-polyester-recycling-circ-partnership-investment-far-eastern-group-512485/
[105] Interview with Syre staff member, August 2024.
[106] https://sifted.eu/articles/harald-mix-aira-northvolt-green-steel; https://sifted.eu/articles/vargas-harald-mix-h2-green-steel-northvolt.
[107] https://sourcingjournal.com/sustainability/sustainability-news/hampm-group-600m-circular-recycled-polyester-venture-syre-textile-recycling-vargas-holding-498357/

3 years to hit scale. It also aims to provide a plug-and-play solution for the existing textile supply chain, requiring no infrastructure modifications for mills to wrestle with.[108]

Syre is starting recycling operations with post-industrial waste, as post-consumer waste is not yet available from their point of view. It is in the process of securing feedstock contracts, so its raw material supply chain is not yet clear. It aims to sell its recycled polymers to other industries in addition to apparel: home textile, automotive, hospitals. The technology allows to use feedstock from any industry and produce recycled polymers that can be used for anything.

Syre is counting on a green premium.[109] This is probably more feasible for Syre because H&M is a major investor in the company and secures demand at least in the initial stage. The business model would be more profitable if it included the yarn production stage, but Syre does not yet have that expertise and would need to form a partnership.

5. CHALLENGES TO COMMERCIALIZING GREEN FIBERS

The summary of issues facing fiber tech firms in the regenerative cellulose (cotton textile recycling) segment is based on the cases above as well as interviews with Birla, an Indian fiber company that produces viscose and lyocell, and is working with at least five regenerative cellulosic fiber technology firms to produce their fibers (Renewcell, Saxcell, Nanallose, Sodra and Evrnu), the founder of Nanollose, a former employee at Spinnova, and a fiber development specialist at the Research Institutes of Sweden (RISE).

The main challenge is the price of regenerative cellulosic fiber based on cotton textile recycling, which is 35-40% higher than virgin lyocell and viscose, due to the costs of starting a new fiber tech company and the costs of feedstock being higher (for now). The cost of feedstock is the costs entailed in textile waste collection, sorting and fiber segregation. This also applies for polyester textile-to-textile recycling companies. Currently, the infrastructure for post-consumer textile waste is still small and mainly oriented around secondhand. The completion of textile waste infrastructure in EU member states in 2025 should improve this situation. However, some observers noted that a technical AI revolution was needed in the sorting step to increase efficiency, by increasing the speed, reducing the cost of labor, and achieving better accuracy in identifying fibers, combined with transparency on the fibers that are in clothing and better designing for recycling.

The global market for viscose and lyocell is a small percentage of the total, around 6 percent. Currently, recycled lyocell fibers have to be blended with other fibers and are not a direct substitute for cotton, which is 28% of global fiber market. More R&D is required in fiber technological development so that recycled fibers have a greater ability to substitute for cotton and thus better ‘drop’ into global supply chains.

[108] https://sourcingjournal.com/sustainability/sustainability-materials/syre-renewcell-textile-recycling-h-and-m-circularity-503775/

[109] https://sourcingjournal.com/topics/raw-materials/circular-polyester-material-innovation-textile-circ-ambercycle-syre-re-up-519572/#:~:text=Most%20circular%20polyester%20purveyors%20are,increase%20its%20capacity%20with%20a

One key challenge at this moment is that brands do not have the incentive to shift more than a small percentage of their fiber portfolio to green fibers, as Extended Producer Responsibility policies are not yet in place. Additionally, the time that it takes apparel buyers to try new fibers in their global supply chains is very slow: 9-24 month cycle. Therefore, buyer demand is low. While some brands signed letters of intent (LOIs), these LOIs were not binding hence brands did not take up the envisioned volumes. It seems that as of now, apparel buyers just want a little recycled lyocell to say their product is circular and achieve the right costing. This inhibits achieving scale to make it profitable for the pulp producers and the fiber spinners. Birla is only able to produce its recycled lyocell fiber Reviva because it is only one out of many fiber in its business portfolio of fibers and does not account for the bulk of its sales. These factors undermined Renewcell, in combination with its early IPO that led investors to push short term demands and have caused Spinnova to seek other revenue flows such as licensing its equipment. Infinited is moving more slowly and seems to be avoiding these problems, but we need time to tell. Infinited did not seek an IPO for financing, which allows it to more slowly, and its technology and product seem to produce a more profitable business model, as it can use waste will a lower cotton percentage, its Infinna fiber is more 'drop in', and it is marketed as a cotton replacement.

The highest need is in polyester textile-to-textile chemical recycling and it seems to be the preferred option of brands given the scale needed to replace virgin polyester, but developments have been moving more slowly in this technology category. The major challenge is the low price of virgin polyester and the high cost of recycled polymers. One apparel brand that we interviewed noted that brands would pay a maximum 10% premium over the cost of virgin polyester.

Polyester textile recycling is not only happening in the US and EU, but also in China and other East Asian countries. One sportswear apparel brand that we interviewed noted that the Chinese firm Jiaren currently sets the global benchmark in terms of the price of recycled polyester, at 'less than 10 cents per kilo'. Notably, Jiaren was the first Chinese firm that started polyester recycling using a glycolosis technology and pre- and post-consumer textile was as feedstock. It licensed the technology in 2023 from a Japanese joint venture firm with expertise in an organic compound used for the chemical decomposition. Jiaren specializes in operating chemical recycling plants. In Taiwan, the move into polyester textile recycling is being driven by incumbent polyester spinning and fabric companies like Far Eastern. We also see some movements by chemical incumbent companies such the German firm BASF to move into polyester textile recycling, but it plans to create its supply chain in China, where most of the polyester production is based.

A big issue for polyester recycling firms, as it is for the regenerative cellulosic ones, is financing, but polyester firms must hit the scale with which to compete with virgin polyester (in the absence of any government regulations that would change the costing or use of virgin polyester). Venture capital was available to green fiber tech companies for a specific time frame, but its attention on green fiber tech was shortlived. Furthermore, venture capital can only provide seed funding for the lab and pilot stages and not for the commercialization stage that requires investments in large scale manufacturing plants, which cost around 400 million USD or more and which have to be built to the requirements of the technology and cannot be existing factories. In all three meta-technologies, venture capital helped create all the startups in the EU and US captured in the mapping but many of them struggled to acquire subsequent financing and that has stalled, unable to enter the commercialization stage. A set of buyers co-invested in these startups because they wanted to get some exposure to the new technologies and fibers. Bank financing is expensive and requires proof of demand and thus strong off-take agreements, which most apparel buyers are hesitant to give.

This financing situation leads to a chicken-and-egg problem, where green fiber tech startups need price parity to compete with 'brown' (conventional) fibers, but to reach price parity they need scale and for scale they need demand and financing, but for financing they need demand and thus price parity. Incumbent firms have the resources, but generally they are not making investments in green fiber technologies because of the risk on demand. The exception here is AeoniQ. Notably, the green fiber tech start-up that has the soundest financing and seems able to scale, Syre, which is also in polyester textile recycling, is the initiative of an apparel buyer combined with a patient capital equity firm specializing in green technologies. Thus, it is the exception that probably proves the rule.

Lastly, the firm case studies show that start-ups founded by scientists struggle to scale because they lack industrial expertise in textile and garment production and global supply chains, which also shapes their business models. Many startups that own patents will not survive and end up selling their technology outright or turn to business models based on a licensing tech model to raise money (like Spinnova). Green fiber tech firms that have turned to partnerships and joint ventures with existing textile and apparel firms may do better. This provides opportunities for textile and apparel firms to form partnerships with new fiber tech firms or leverage their tech to move into fiber production, and thus potentially gain more power in the global value chain if they could build industrial clusters (like China has done in battery technologies).

6. CONCLUSION

The main driver to move from the laboratory to the market with green fiber technologies has been EU regulations, and to a lesser extent US regulations, that aim to change textile use. These regulations did not directly create market demand for 'green fibers' but rather emphasize transparency in the fiber and production process, implicitly relying on consumers to change market demand through their consumer behaviour. Thus, the EU is leading on market creation for green fibers, but it is weak. EU regulations were driven by multiple motivations, including trying to re-shore textile production in Europe, although further research is needed on this aspect. But what is clear is that EU policies are not focused on creating demand for green fibers through policies directly targeting the creation of market demand. There is also not a broad objective to replace dependence on the petro-chemical industry, for example, which is a broader take on the replacement of fossil fuel in plastics. If that was the objective, then biotech and recycling firms would be supported to use biosynthetics and repolymerization on a bigger scale. Rather, current EU policies are segmented into different industries, the EU textile strategy focusing on textile-to-textile recycling, which can complicate the business strategies of some fiber companies.

Current regulations do not compel brands and retailers to switch to more than a small percentage of their fiber to green fiber. The responses of global apparel brands and retailers to the new EU regulations include shifting to 'preferred' fibers, adopting 'green' fibers in small, pilot collections for experimentation and marketing purposes and some equity stakes in green fiber technology firms. This is because incumbents (chemical firms and apparel buyers) have few incentives to change the existing industry configuration and to take (financial) risk that hits their margin. New firms have greater incentives to commercialize green fiber technologies, as shown by the fact that more than hundred start-ups have emerged or moved into this space. But they face greater challenges with commercialization due to the large financing requirements and market risk, and they lack the financial flows and diversified portfolios of incumbent firms.

In the absence of stronger government policies to create market demand for green fibers, green fiber tech firms generally will continue struggle to get a premium on their fibers (price above that of conventional fibers) that would allow them to compete, given that apparel buyers hold the most power in apparel global supply chains. To capture a premium, or to reduce costs by enhancing economies of scale, fiber tech companies would have to pursue one of two strategies, which boost their position and demand in global supply chains. They could 'go vertical': pursue vertical integration in which they carry out more of the steps in the global supply chain, at least up to producing the fabric. This option could be achieved through mergers and joint ventures. The other option is 'go horizontal': create clusters of firms along the supply chain at the country level and effectively achieve the same result as vertical integration but through industrial clusters. This option requires inter-firm collaboration, and probably a core firm to lead the collaboration and anchor the eco-system.

REFERENCES

Abernathy, F. H., Dunlop, J. T., Hammond, J. H., & Weil, D. (1999). *A stitch in time: Lean retailing and the transformation of manufacturing: Lessons from the apparel and textile industries*. Oxford University Press.

Chandler, A. (2004). *Shaping the Industrial Century: The Remarkable Story of the Evolution of the Modern Chemical and Pharmaceutical Industries*. Harvard University Press.

Chandler, A. (2005). *Inventing the Electronic Century: The epic story of the consumer electronics and computer industries*. Harvard University Press.

Dosi, G. (1984). *Technical change and industrial transformation: The theory and an application to the semiconductor industry*. London: Springer.

Hobday, M. (1995). *Innovation in East Asia: The challenge to Japan*. Cheltenham: Edward Elgar.

Jansen, A. & Breznitz, D. (2024). Effectively financing private sector innovation? Toward a conceptual policy framework. *Science and Public Policy* 51: 580-592.

Leonard-Barton, D. (1992). Core capabilities and core rigidities: A paradox in managing new product development. *Strategic Management Journal* 13(S1), 111-125.

Lüthje, B., & Zhao, W. (2024). Manufacturing Competency: Roots of Competitive Advantage of Chinese Electric Vehicle Battery Industry. Preprint, accessed via doi:10.20944/preprints202405.0502.v1.

Maile, F., & Staritz, C. (2024) Towards shorter and greener supply chains? Understanding shifts in the global textile and apparel industry. In: Sustainable Global Supply Chains in times of geopolitical crisis. Research Network Sustainable Global Supply Chains, Annual Report 2023. Accessed via https://www.sustainablesupplychains.org/wp-content/uploads/2024/01/SustainableGlobalSupplyChains-Report2023.pdf

Maile, F., & Whitfield, L. (forthcoming a). Capturing value in a buyers' market: Supplier value capture trajectories in apparel global supply chains.

Maile, F., & Whitfield, L. (forthcoming b). Rethinking upgrading in apparel GVCs: product innovation cycles and strategic partnerships with buyers.

Malerba, F. (1985). *The semiconductor business: The economics of rapid growth and decline*, Madison: University of Wisconsin Press.

Malerba, F. (2007). Innovation and the dynamics and evolution of industries: Progress and challenges, *International Journal of Industrial Organization* 25(4), 675-699.

Mazzucato, M. (2016). From market fixing to market-creating: a new framework for innovation policy, *Industry and Innovation* 23(2), 140-156.

Milberg, W. (2013). *Outsourcing Economics: Global Value Chains in Capitalist Development*, Cambridge: Cambridge University Press.

Schumpeter, J. (1954). *Business Cycles: A theoretical, historical and statistical analysis of the capitalist process*. Volume One. Martino Fine Books.

Taplin, I. M. (2014). Global commodity chains and fast fashion: How the apparel industry continues to re-invent itself. *Competition & Change* 18(3), 246-264.

Thurbon, E., Kim, S. Y., Tan, H., & Mathews, J. A. (2023). *Developmental environmentalism: state ambition and creative destruction in East Asia's green energy transition*, Oxford: Oxford University Press.

APPENDIX: LIST OF INTERVIEWS

Firm	Position	Date	Location
Renewcell	COO	January 2023	Online
Birla	Joint President of Brands and Retail	June 2024	Online
Nanollose	CEO	June 2024	Online
Ambercycle	Former sales manager	August 2024	Online
Syre	Sustainability and Public Affairs manager	August 2024	Copenhagen
Re&Up	CEO	August 2024	Online
Crystal Group	Sustainability Officer	August 2024	Hong Kong
Puma	Sourcing officer	August 2024	Hong Kong
Epic	Fabric Research & Development Officer	August 2024	Hong Kong
Spinnova	Former head of Business Development	August 2024	Online
Textile firm	Former head of sustainability	August 2024	Online
Hansae	CEO	August 2024	Seoul
Research Institutes of Sweden (RISE)	Director Fiber Development	September 2024	Online
AeoniQ	Director Business Development	September 2024	Online