DISCOVERY REPORT

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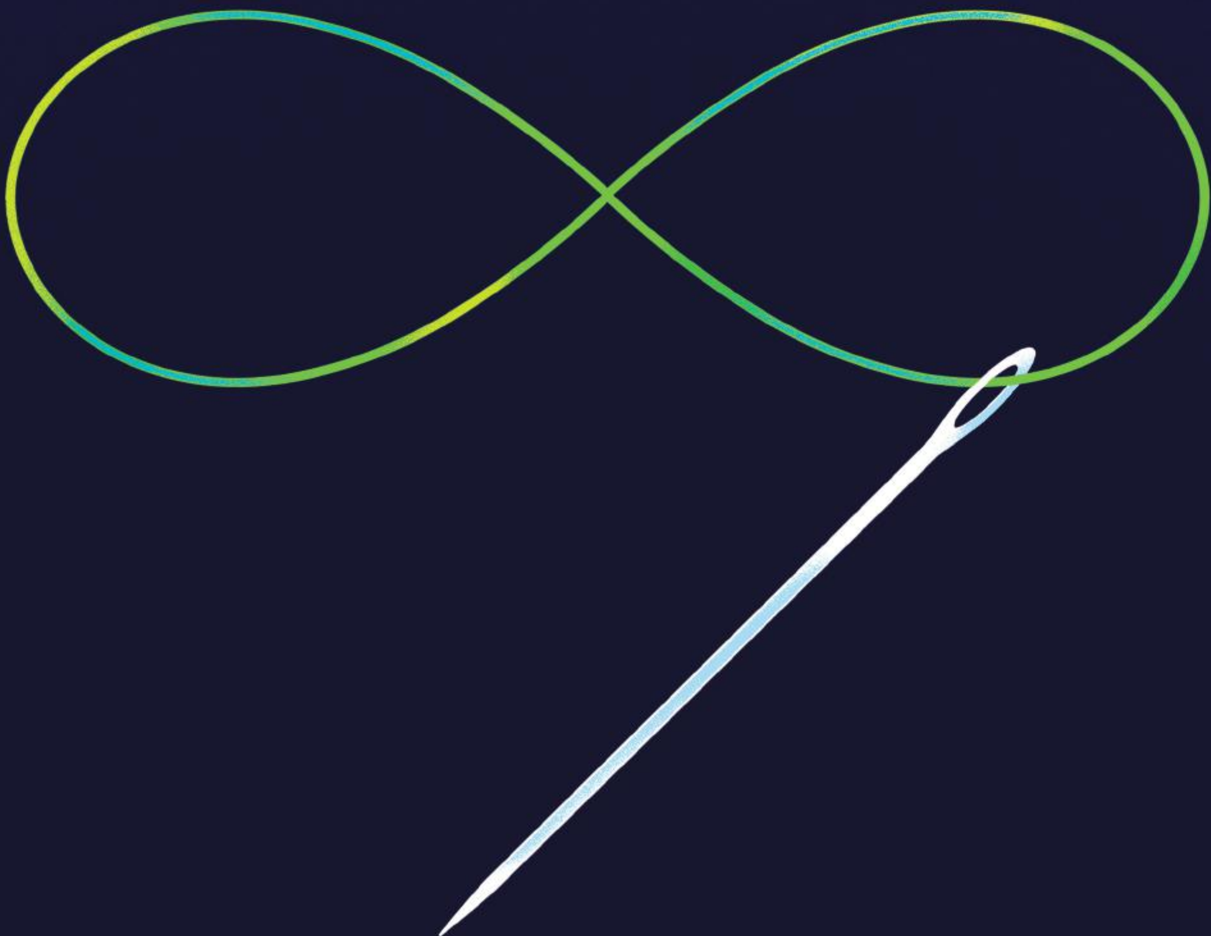

The future of sustainable textiles

Chemistry is closing the loop on fashion waste

Published by
c&en

$39.99

The future of sustainable textiles

The fashion industry is all about the latest trends, and sustainability is in. Websites for sneakers, sweaters, and even wedding gowns attest to brands' use of recycled materials, partnerships with textile recyclers, or marketplaces for gently used purchases.

Make no mistake, however: the textile industry as a whole is still causing harm to our planet. Clothing represents about 60% of global textile use, and clothing production has doubled in the past 15 years, according to the Ellen MacArthur Foundation. It's challenging to capture the scope of the problem, because labyrinthine textile supply chains span the globe. Estimates of the industry's carbon footprint range from 4% to 10% of global greenhouse gas emissions, according to the *Harvard Business Review*.

It's troubling to think that a polymer contributes to the problem. Polyester is a triumph of materials science. It yields long-lasting fabrics that are wrinkle and shrink resistant, that wick away sweat, and that can be dyed to any color in the rainbow. Over half of all textiles contain it. But it sheds harmful microfibers into the environment. And because it is inexpensive, polyester is a key component of fast fashion's stylish yet all-too-disposable clothes.

There's reason to be hopeful. This report examines how chemists and entrepreneurs are rethinking textiles. You'll meet entrepreneurs finding ways to recycle polyester clothes over and over again, scientists dyeing fabrics without using precious water, companies making synthetic fabrics without petroleum feedstocks, and more.

Contributing editor Carmen Drahl, who has covered organic chemistry and green chemistry for C&EN, edited this report. It includes a reading list of papers and patents curated by our sources, as well as by information scientists at the CAS division of the American Chemical Society.

As an ACS member, you get exclusive access to the Discovery Report, a quarterly publication bringing you cutting-edge research defining the chemical sciences and our industry. Look for the next one in the third quarter of 2022.

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INSIDE

Published by
c&en

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CHEAT SHEET

5 questions and answers about sustainable textiles

Q. How does the textile industry impact the environment?

» **It consumes nonrenewable resources.** Synthetic fibers such as polyester and nylon come from petroleum feedstocks. Cotton crops consume an estimated 6% of global pesticide production. Other chemicals act as dyes, tanning agents, or finishing agents.

» **It requires a great deal of water.** Unsustainable cotton farming contributed to shrinking the Aral Sea in central Asia, once the world's fourth-largest lake, and led to ecosystem destruction.

» **It generates a lot of waste.** The world disposes of 92 million metric tons (t) of textiles annually, or about twice the weight of a midsize car every second. Roughly 73% of each year's textile waste goes to landfills or incinerators. Microfibers shed by textiles harm wildlife and have polluted the remotest corners of the world.

Q. What human factors contribute to waste in fashion?

» **Fast fashion increased clothing consumption.** The frequent turnover of inexpensive styles entices people to buy new things rather than mend old ones. The average number of times a garment was worn before being discarded fell by 36% between 2002 and 2017.

» **True recycling is practically nonexistent.** Less than 0.5% of postconsumer textile waste is recycled into similar-quality applications. Most recycled fibers are of insufficient quality to make new clothes, so they end up in rags or stuffing.

Q. How is chemistry developing solutions?

» **Renewable sources of yarns and fibers are emerging.** Entrepreneurs are developing fabric from sugars or harnessing microbes to grow raw materials.

» **Chemical recycling technologies can extract the molecular building blocks from common fibers to make new textiles.** Companies say that yarns made with their platforms have performance comparable to that of newly manufactured fibers.

» **New leather alternatives avoid land use, animal slaughter, and tanning chemicals.** Scientists are turning to plants, fungi, and even fish skins to create strong, supple materials.

» **Some dyeing options no longer require water, or they avoid petrochemical inputs.** Start-ups are depositing color with supercritical carbon dioxide or natural dyes.

Q. What challenges stand in the way of recycling?

» **No company is yet capable of recycling every fiber that goes into textiles.** Nor are companies producing commercially viable amounts of the fibers they do recycle. In addition, some fabric blends cannot be recycled.

» **Recyclers' sorting capabilities must improve to handle higher volumes of material.** Disassembling seams, zippers, and embellishments is labor intensive.

» **Recycled fibers are not yet cost competitive with new fibers.** The packaging and textile industries are competing for limited stock of recycled synthetic polymers, which is driving prices up relative to new material.

» **More recycling cannot fix overproduction.** The world must develop new business models that support slower fashion consumption.

Q. What's next for sustainable textiles?

» **Regulations are coming.** The European Union has proposed that its member states collect, sort, and recycle all textile waste by 2025.

» **Some sustainable clothes and accessories are arriving in stores.** Launches of ecofriendly fabric and leather products will test consumers' interest and determine acceptable price points.

» **By 2030, there will be 5.4 billion people in the global middle class, nearly double that in 2015.** These consumers will want the trappings of a middle-class closet, which makes the need for a sustainable, circular textile industry all the more urgent.

8 experts identify opportunities for reducing textiles' impact on the environment

Guillaume Boissonnat

» Chief science officer, Pili

Guillaume Boissonnat and his team are on a mission to reduce the garment industry's carbon footprint and water pollution. Headquartered in Toulouse, France, his start-up is producing biobased dyes and pigments to replace petrochemical colorants for textiles.

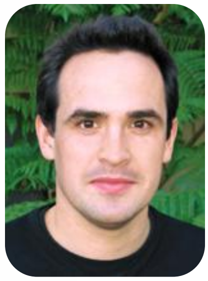
"At Pili, we've decided that we cannot change everything," he says, "but as chemists and engineers we can focus on some of the processes used in the textile industry, especially those of dyeing textiles and producing dyes."

Dyeing generates a lot of pollution. Synthetic dyes, solvents, and other chemicals needed to color clothes are energy intensive to make, while the dyeing process creates immense amounts of chemical-laced wastewater.

Pili is engineering bacteria to brew dyes from sugar in fermentation tanks. The bacteria capture carbon dioxide while they grow, and because the process works at room temperature, it uses less energy. Compared with petrochemical dyes, the system reduces CO_2 emissions by 50–90% and water usage by 80%. "We use less toxic chemicals, less solvents, and have less discharge into the environment," Boissonnat says.

A pilot plant being built near Lyon, France, will make Pili's first commercial product, a blue pigment, that will go on the market by the end of the year. Boissonnat says the company already has agreements with several textile brands. After it makes the first metric ton (t) of the pigment this year, the firm's plan is to scale up to 50 t in 2023.

> **"We cannot change everything, but as chemists and engineers we can focus on some of the processes used in the textile industry."**



Mark Browne

» Ecologist, University of New South Wales

For Mark Browne, sustainability is a word that's best avoided. "It means different things to different people, and that increases the capacity for confusion and greenwashing," he says. Instead, scientists should be focusing on a well-defined problem, which for him is microfibers shed from synthetic clothing.

Browne's 2011 study was the first to show that those fibers are the largest source of plastic pollution in the oceans. Over a decade later, he says, response from producers and regulators remains muted.

Tackling pollution involves avoiding a pollutant, intercepting it, or trying to reengineer the system that creates or eliminates it. For synthetic microfibers, strategies could include using natural fibers that biodegrade or durable fabrics that don't shed; intercepting via washing machine filters; or redesigning washing machines so they don't produce as many microfibers. He is analyzing several strategies and evaluating their cost effectiveness.

Browne's team published a study in 2020 of washing machine filters available on the consumer market. The filters allow up to a third of polyester fibers to reach the wastewater stream; smaller filter pores hold back more cotton fibers, but not polyester, which is the material of concern. Basic research like this can provide "evidence to understand and manage the problem," he says, but there is a lack of willingness to support it.

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Clothing companies typically ignore the problem, declare it unsolvable, or do their own research, which can involve unscientific, unreplicated experiments, Browne says. The result is misinformation and greenwashing about sustainable apparel, which he says hurts people as well as the environment. “The consumer can only make choices based on information they’re given,” he says. “People are asking what type of clothing to wear, or what filter or washing machine or detergent to use. We haven’t been able to give them evidence-based solutions. I feel sorry for the public. They’ve been let down by the science and engineering community, industry, and government.”

Hanna de la Motte

» **Vice president, business and innovation in material transition, RISE Research Institutes of Sweden**

Hanna de la Motte is excited about Sweden’s sustainable textile developments. The nation’s large forestry industry provides infrastructure and expertise in chemically processing wood to derive cellulose. De la Motte and others are translating this knowledge to recycling the cellulosic fibers cotton, viscose, and lyocell.

Two Swedish companies, Södra and Renewcell, are building commercial-scale plants for recycling waste cotton textiles (see page 8). A decade of research by de la Motte in collaboration with Chalmers University of Technology underpins Södra’s technology to extract and recycle cotton from cotton-polyester blends.

“We need to make natural fibers with improved properties that could compete with strong synthetic fibers.”

De la Motte is also tackling synthetic fibers with scientists at Chalmers University of Technology. The team employs gasification to break down blended textiles into methanol or synthesis gas that could become reusable feedstock. They are now assessing whether such a gasification plant should be built close to waste processors that provide the textile waste or chemical industries that can use the feedstocks. “The process might not have the best yield, but in a world where we need to think about how to use our resources, it might still have a place in the market,” de la Motte says.

She coordinates another project to analyze the recyclability of viscose and lyocell to make new fibers. In this initiative, RISE researchers are developing new spinning technology to make cellulosic fibers that are stronger than cotton. To increase the market share of biobased textiles, she says, “we need to make natural fibers with improved properties that could compete with strong synthetic fibers.”

Tiffany Hua

» **Analyst, Lux Research**

Tiffany Hua’s job is to keep her finger on the pulse of alternative materials in the apparel industry and ask questions. Many brands are making commitments to reduce waste, emissions, and pollution, but Hua looks for companies to turn words into work. Instead of broad commitments, she says, “what’s really impactful is realistic goals, and strategies and actions backing them.”

Technologies on the horizon should counter some of fashion’s environmental impact, she says. Start-ups like LanzaTech and Fairbrics are creating polyethylene terephthalate (PET), known as polyester in fabrics, from captured carbon emissions. This carbon-capture PET, as well as biobased PETs made from corn or soy, are drop-in replacements for petrochemical PET. But Hua says these materials cost more than petrochemicals and do not biodegrade. Biobased PET also brings up land use and water runoff issues: “So the question is, ‘Are they better and worth the cost?’”

Hua is keeping a close eye on developments involving polyhydroxyalkanoate (PHA). Like PET, PHA is recyclable and has found use in packaging. Unlike PET, PHA is biodegradable and made through bacterial fermentation. The Fashion for Good project is trying to spin and extrude PHA into fibers for textiles, while Nike and start-up Newlight Technologies are partnering to develop PHA fibers. Hua thinks PHA fabrics show promise for reducing emissions and microplastic pollution but says the polymer’s degradation lifetime and interactions with marine ecosystems need further evaluation.

Cutting waste will be a bigger challenge than developing new fibers, she adds, noting that waste reduction requires better product design and messaging. Corporations drive consumer culture, according to Hua. “Product design changes behavior,” she says. “You can encourage reuse and resale.”

Lisa Kennedy

» **Senior director of business development, Genomatica**

Lisa Kennedy believes that manufacturers don’t have to rip up their chemical blueprints and start from scratch to make consumer products sustainable. Genomatica harnesses engineered microbes to make versatile chemical intermediates from plant-based sugars instead of fossil fuels. By producing drop-in molecules that can be substituted in supply chains without extensive development and testing, Genomatica aims to ease producers’ transition to renewable materials. Manufacturers can use “the exact same products but made in a better way,” Kennedy says.

The San Francisco–based company’s products are designed not only for apparel but for the plastic packaging, cosmetics, and nutrition industries. The main product of its fermentation technology is 1,4-butanediol, a building block of spandex as well as plastics for nontextile applications. Genomatica is partnering with Cargill to build a plant capable of producing 65,000 t per year; the facility should begin operating in 2024.

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Additionally, Italian bioplastic maker Novamont has licensed the technology to make 30,000 t annually.

A big R&D effort now is advancing the development of biobased precursors for the two major types of nylon, Kennedy says. Pilot-scale facilities built with industry partners are producing tons of both precursors for quality testing, Kennedy says. Meanwhile, Genomatica and apparel brand Lululemon will collaborate on creating a plant-based nylon—Lululemon's most-used synthetic material—to help meet the brand's goal of using completely renewable and recycled materials by 2030.

Adrián López Velarde

» Cofounder, Adriano Di Marti

Three years developing fabrics for the fashion and auto industries gave Adrián López Velarde a firsthand view of the environmental impact these materials have. That led him and Marte Cázarez to start a company—Adriano Di Marti—that makes a leather alternative, called Desserto, from the prickly pear cactus (see page 14). Today, the Tesistán, Mexico–based company makes cactus leather products for Adidas, Fossil, Givenchy, and Mercedes-Benz.

Adriano Di Marti's team extracts proteins and fibers from mature cactus leaves to produce a resin. Mixing the resin with organic pigments and plant-based oil additives creates a biopolymer that the company uses to coat recycled cotton or polyester fabric. The resulting material closely resembles animal leather in texture and feel, which appeals to designers, López Velarde says. "You have to have a balance between aesthetics, performance, scalability, and sustainability."

The cactus requires no irrigation, pesticides, or fertilizers. This results in reduced water and energy use, carbon emissions, and agricultural runoff compared with leather or its polyurethane substitutes, López Velarde says. By increasing cactus-based content and using renewable energy in production lines, the company plans to make new formulations even more sustainable.

Facilities in Mexico and Europe make about 6,720 t of Desserto annually. The focus now is to produce the material near its end users to reduce transportation cost, emissions, and lead times, López Velarde says: "We're trying to make the materials as affordable and available as possible so it's a no-brainer for companies to switch."

Ulrich Scherbel

» CEO, AMSilk

Strong and lightweight, stretchable and biodegradable, spider silk has properties that put petroleum-based products to shame. Ulrich Scherbel takes pride in AMSilk's use of environmentally friendly methods to make synthetic spider silk proteins. The 14-year-old German company produces the proteins via *Escherichia coli* fermentation of plant-based carbon sources (see page 14). The process requires a lot of water, but Scherbel says the used resource contains no chemicals and "can be put back into the river it came from."

AMSilk's protein has been blended with polyamide and fashioned into wristbands of some Omega watches. Threads of synthetic spider silk will be woven into sports shoes due to launch later this year. Apparel products will follow in 2023.

To develop tailor-made spider silk protein products for a customer, AMSilk turns to established protein manufacturers—companies that already make billions of metric tons of vitamins, amino acids, and pharmaceutical proteins. "AMSilk produces very complicated proteins," Scherbel says. "We teach people who produce simple proteins how to produce our proteins."

"We're not a sci-fi start-up" based on some far-fetched fantasy, Scherbel says. "Customers can order quantities because capacity doesn't have to be built up. It's already there. Scale-up is quite agile."

AMSilk has roughly 50 consumer projects in the pipeline and is further ramping up production. Meanwhile, Scherbel envisions ways to reduce the company's carbon footprint even more. "In the future, the carbon we use could come from captured CO_2," he says.

Julie Willoughby

» Chief scientific officer, Circ

Fast fashion, while making stylish clothing affordable, has created waste and emissions that are difficult to counteract, Julie Willoughby says. By recycling cotton-polyester blends—today's predominant fabric for apparel—with its proprietary hydrothermal recycling technology, Circ hopes to turn landfill- or incinerator-bound textile waste into a resource. Willoughby anticipates that the Danville, Virginia, start-up's recycled material will be cost competitive with new raw materials. "We are trying to protect the planet from the high environmental cost of fast fashion," she says.

Mechanical recycling can keep blended textiles from landfills, but it can't separate the material into its components. And recycled blended material has degraded properties. Circ's process uses water under heat and high pressure to liquefy and break down polyester in blended textiles without damaging the cotton fibers (see page 15). The cotton is mechanically separated from the liquefied polyester and turned into cellulosic fiber using processes similar to those for making lyocell. Polyester monomers recovered from the liquid are again polymerized into polyester fibers.

Willoughby says Circ's vision is a circular textile economy that lets consumers enjoy the performance, feel, and aesthetics they have come to love without the need for new raw materials. "You can wear the same clothes for life by continuing to regenerate clothing," she says.

With upcoming Series B funding and a recently announced partnership with Austrian technology group Andritz, Circ plans to open its first commercial plant, capable of recycling 200 t of textiles a day, by 2024. ■

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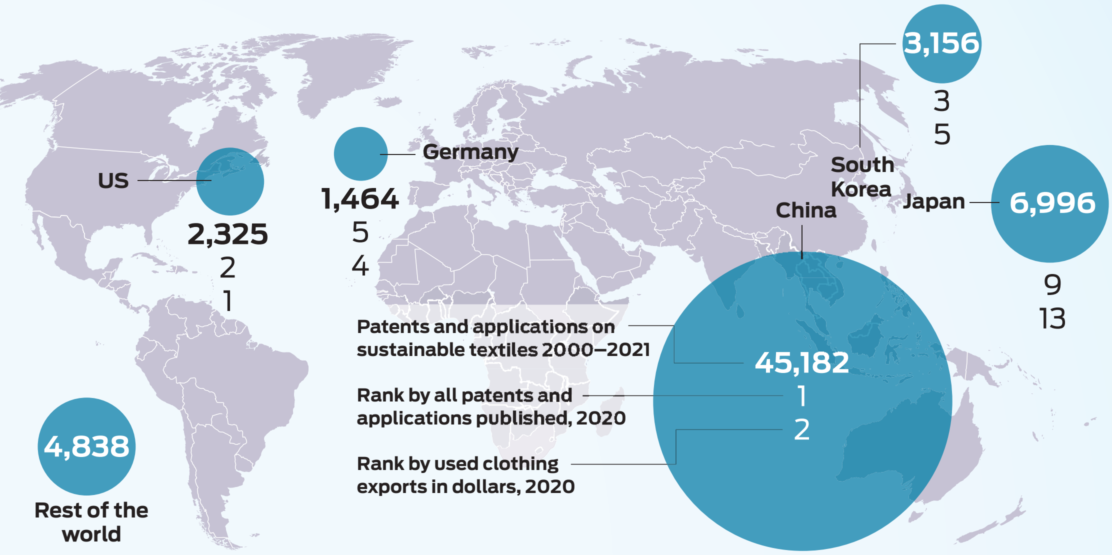
Discover trends in sustainable textiles

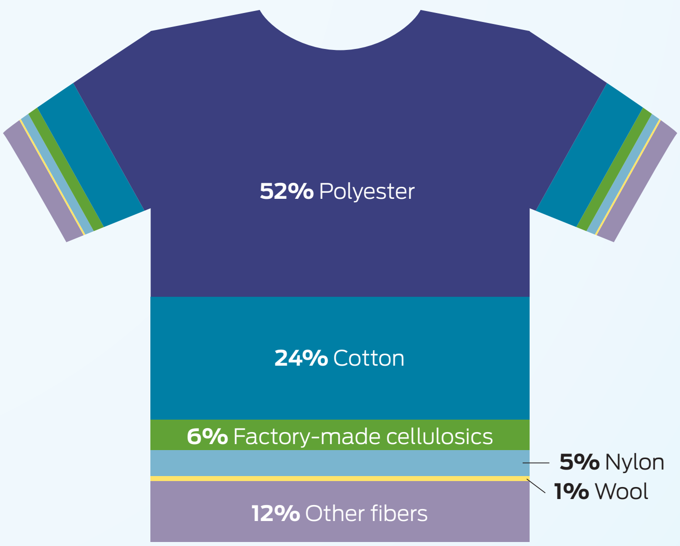
Who's who

The US exports more dollars' worth of used clothing than any other country, but it is a distant fourth in filing patents relating to sustainable textiles and fibers.



The market

Polyester is the dominant fiber in the global textile industry.



Market size in 2020 = 109 million metric tons

Sources: CAS Content Collection, Ellen MacArthur Foundation, *Nat. Rev. Earth Environ.*, Observatory of Economic Complexity, Textile Exchange.
Notes: CAS information scientists searched patents and publications containing the concept of sustainable textiles from 2000 to 2021. "Publications" include journal publications, conference reports, books, dissertations, reports, and preprints. Patents may mention more than one type of technology.

Sustainable textile stats

Boost your knowledge with our selection of facts and figures.

73%
Share of waste textiles that were incinerated or dumped in a landfill in 2017

<0.5%
Share of old clothing that was recycled into new clothes in 2021

92 million
Metric tons of waste textiles generated annually

36%
Decrease in the average number of times a person wore a garment before discarding it, 2002–17

$500 billion
Estimated value that the textile industry loses every year because of underused clothes and a lack of recycling

1%
Proportion of used clothing exports originating in China, 2010

6.4%
Proportion of global used clothing exports originating in China, 2015

ANALYSIS

Chemical recycling technologies could play a key role in slashing the textile industry's environmental footprint.

Transforming textiles

ALEX SCOTT, C&EN STAFF

Patrik Lundström is pleased with his new pair of Levi's 501s. "The touch and feel is exactly the same as your cotton jeans," he says. Lundström is CEO of Renewcell, a Swedish start-up that has created Circulose, a cellulosic fiber made by chemically recycling postconsumer waste cotton. About 16% of the cotton in Lundström's Levi's has been replaced with Circulose. Lundström is heralding the switch as a new start for the unsustainable textile industry. Unlike garments made of virgin cotton or polyester, those made from Circulose have a "fashion footprint" of almost zero for waste creation, climate impact, water consumption, microplastics generation, and deforestation, the company claims.

The textile industry, with its ever-growing environmental footprint, is crying out for sustainable technologies. A wave of new companies is responding with chemical-based recycling technologies for all the main fibers, including cellulosics such as cotton, and synthetics like polyester and nylon.

But no single company yet has the complete process to recycle all fibers. And none are producing commercially viable amounts of recycled fibers yet.

Indeed, stakeholders, including fashion companies and waste collectors, face myriad challenges if they are to deploy such technologies at a meaningful scale. Some of the issues are technical, such as the unsuitability of certain types of textile waste to most recycling processes. A lack of adequate supplies of cellulosic textile waste for recycling also looms. If the sector's key actors pull together, though, new recycling technologies could play a major role in helping the textile industry slash its environmental impact.

Consumers around the world are buying clothing and other textiles at such a scale that the sector's environmental footprint is now the fourth largest, after food, housing, and transportation, according to the Ellen MacArthur Foundation, a UK think tank promoting the circular economy.

The world's multibillion-dollar textile industry generates 1.2 billion metric tons (t) of CO_2 annually, more than the emissions from all international flights and maritime shipping combined, according to the Ellen MacArthur Foundation. Other impacts include the water and pesticides used to grow cotton, water pollution during fiber spinning and dyeing, and the release of microplastics into the oceans from the household washing of garments made from synthetic fibers.

Global fiber production in 2020 was 109 million t, of which more than half was polyester and about a quarter was cotton, according to a report on the fiber market by Textile Exchange, a group promoting sustainable textile manufacturing. Less than 0.5% of postconsumer textile waste is being recycled, it says.

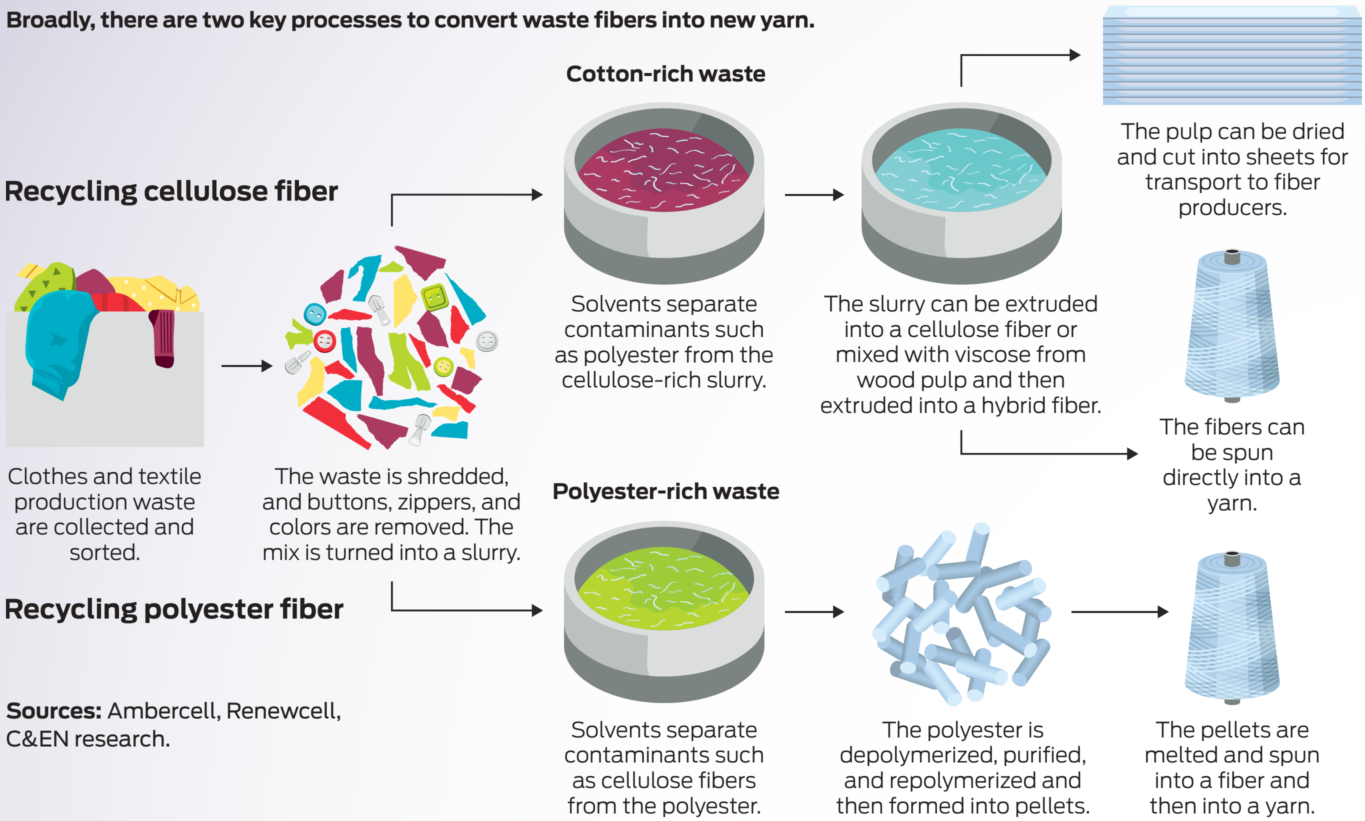
"The house is on fire," says Holly Syrett, impact programs and sustainability director for Global Fashion Agenda (GFA), a Copenhagen, Denmark–based think tank that for more than a decade has been promoting sustainability in the fashion industry. About 73% of all textile waste generated annually is incinerated or dumped in a landfill, according to the Ellen MacArthur Foundation. Textile waste will rise to 134 million t by 2030, the foundation predicts.

Existing technologies and systems are not solving the problem. Mechanical

CREDIT: MIKE REDDY

Old clothes to new fibers

Broadly, there are two key processes to convert waste fibers into new yarn.



Sources: Ambercell, Renewcell, C&EN research.

recycling of textiles, which has been around for years, is not a fully sustainable option because the mixture of colors and fiber types typically destines textiles for downcycling into low-value products such as furniture stuffing. Such activity, along with the reuse of clothing, ultimately delays but does not prevent textiles' becoming waste.

A growing slice of the global fashion industry is working with GFA to remedy these problems. Active companies include clothing retailers Benetton, H&M Group, Marks and Spencer, and Primark. They say they are asking their garment suppliers to adopt recycling as part of a package of waste reduction measures that includes leasing and sharing clothes and designing garments that last longer.

Tackling cellulosics

Clothing companies working with GFA are also funding chemical recycling technology start-ups. H&M, for example, has invested in one of more than a dozen companies in Scandinavia and neighboring Finland that are developing cellulose recycling technologies.

Many firms in this far north region of Europe were spun out of universities that have long researched cellulosic chemistry because they are located near producers of pulp and paper. Universities there that have spun out waste textile recycling technology include Aalto University and KTH Royal Institute of Technology.

Renewcell's Circulose process (see page 16) is similar to that for making viscose, also known as rayon—a cellulosic fiber made from wood pulp.

In the process, the company starts by mechanically shredding and bleaching waste fibers. It then converts the cotton into a dissolving pulp. Synthetic polymers are separated in a solvent-free step before Renewcell dries the bleached waste pulp into sheets for transportation to fiber producers and then yarn makers. “Our customers can mix Circulose with wood pulp or run it at 100%,” says Kristina Elg Christoffersson, Renewcell's chief technology officer.

Chemicals maker Nouryon has agreed to supply Renewcell with the bleaching chemicals hydrogen peroxide and sodium chlorate for the Circulose process. “We use common chemicals. This is why we are able to scale up fast. And we are using conventional reactors and process equipment,” Christoffersson says. Renewcell claims that “nothing we add in follows the product or process water out of the plant.”

Renewcell is due to start up a 120,000 t per year Circulose plant in Sundsvall, Sweden, this year. The plant, which will digest millions of waste cotton garments, will cost about $100 million. Renewcell aims to quickly add to this capacity and has a goal of producing 360,000 t of recycled fiber annually by 2025.

“We are getting so much interest at this point in time,” Lundström said in a recent video briefing on Renewcell's strategy. The firm has already signed a number of deals, including a contract to supply 175,000 t of Circulose over a 5-year period to the Chinese viscose producer Tangshan Sanyou.

Helsinki-based Infinited Fiber is also developing a viscose-type process for recycling cotton and other cellulosic textiles (see page 15). The company's CEO, Petri Alava, says he is hunting for an industrial site that the firm can convert into a demonstration plant with capacity for making 30,000 t of recycled fiber per year.

In Infinited's viscose-like cellulose recycling process, nonfiber elements such as zippers are removed mechanically, and the fibers are shredded. An acid pretreatment followed by an alkaline hydrolysis step separates most noncellulosic materials. The remaining cellulose is reacted with urea to form a cellulose carbamate powder. The powder is dissolved in dilute sodium hydroxide to form a so-called dope solution with a consistency of syrup that can be spun into a fiber ready for yarn making.

"This is technically and chemically quite a simple process," says Sakari Siren, Infinited's chief technology officer.

Many other new companies are also developing cellulose recycling technologies. For example, Nordic Bioproducts Group, a spin-off from Aalto University, has a viscose-type process. Earlier this year it began a technology partnership with Chile's CMPC, the world's third-largest pulp and paper producer.

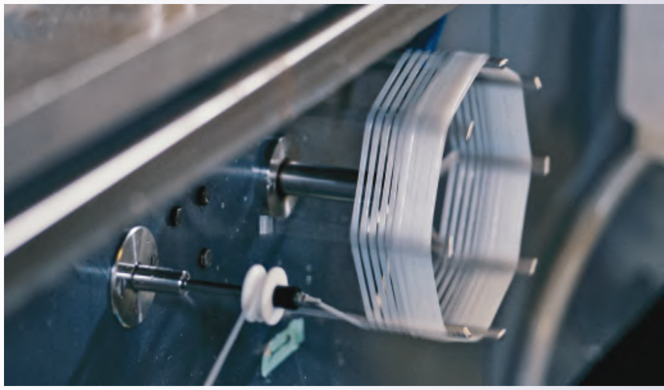
On the other end of the corporate spectrum is Lenzing, an Austrian firm that has been producing viscose since the 1940s. In 2017 it rolled out Refibra, a cellulosic fiber made from 100% cotton waste. Production is based on a dissolving pulp process adapted from the firm's viscose technology. Lenzing currently sells modest volumes of Refibra to 30 clothing retailers, including Patagonia

Renewcell creates a dissolving pulp from waste cotton that forms the basis for new cellulosic fibers.

"Scale-up of chemical recycling technologies is really starting to happen now."

and Levi Strauss. It plans to increase production to 60,000 t per year of a fiber blend with a 30% concentration of Refibra by 2025 at a plant operated by its technology collaborator, the Swedish wood pulp producer Södra.

Companies with nonviscose processes are also looking to scale up. Virginia-based Circ, formerly called Tyton BioSciences, is using subcritical water—water heated under pressure to temperatures above boiling point—to both extract cellulose and depolymerize polyester (see page 6). Circ, which is a partner with Patagonia and the industry initiative Fashion for Good, claims that its process can be run on fiber blends and that the level of its recovery of fibers is more than most other separation techniques.



Nordic Bioproducts makes fiber from its viscose-type pulp process.

Meanwhile, Finland's Ioncell is seeking investment to commercialize a process that uses ionic liquids to dissolve cotton waste so that it can extract hemicellulose fibers, which can be spun into new yarn.

The waste purity problem

While a smorgasbord of technologies for chemically recycling cellulosic waste is emerging, to work at scale, they will need a guaranteed supply of waste cotton with a minimal amount of contamination from synthetic fibers. This is especially true for the Renewcell and Infinited technologies, which can tolerate a polyester content of only 10–15%. And in general, the less suitable the waste fiber is, the more processing steps—and process chemicals—are required.

The sensitivity of textile recycling processes to contamination could be a major issue because, as the European Commission warns in a 2021 report on the circular economy, almost one-third of all textile waste comprises multilayer clothing that can feature three or more fiber types.

Lenzing flags the availability of a suitable textile waste stream as another key issue. For environmental reasons, the company is striving to source cellulosic textile waste that is generated locally. "It does not make sense to transport postconsumer waste around the globe," says Sonja Zak, head of

Renewcell dries pulp made from waste cotton into sheets that are then sent to fiber producers.

Lenzing's circularity initiative. The firm indicates that it will be sourcing postconsumer waste textiles from Europe, while it may get postindustrial waste—scraps of textile waste left after factories make clothes—from Asia.

And looming over the industry is the idea that chemically recycling cellulosic fibers may not be a completely circular process. Although cellulose can be recycled several times, the polymer chain degrades with each repetition, according to the 2017 report by the Ellen MacArthur Foundation. "Hence the quality of the input should be monitored closely," the European Commission (EC) says in a January 2022 report on the effectiveness of textile recycling.

The quality of the fiber that results from recycling is important but is something that companies "are not transparent about," says Sandra Roos, formerly a researcher with Mistra, the Swedish Foundation for Strategic Environmental Research, and now head of sustainability for the Swedish clothing brand Kappahl, in an email.

Roos also warns that the textile industry must focus on more than just fiber recycling if it is to reduce its environmental footprint. Dyeing, for example, has a major environmental impact that needs to be tackled, she says.

The polyester conundrum

If the textile industry is to become truly sustainable, though, it will also have to tackle the environmental footprint of polyester, which is used to make 52% of all textiles. Unlike cellulosic fibers, synthetic fibers, including polyester, are a primary source of microplastics—plastic particles smaller than 1 mm in diameter—which are entering the world's rivers and oceans. Microplastics and microfibers pose a significant risk to the aquatic environment and possibly to human health.

"The number of microfibres released from a typical 5 kg wash load of polyester fabrics was estimated to be over 6,000,000 depending on the type of detergent used," a study published in 2018 in the journal *Environmental Pollution* concludes (DOI: 10.1016/j.envpol.2017.10.057). Common Objective, an organization promoting sustainable textile production, states in an online report that 35% of all microplastics entering the oceans is from synthetic textiles and that most of this fraction is polyester.

While almost no polyester fiber-to-fiber recycling is taking place anywhere, about 7.6% of polyester fibers produced today are derived from recycled beverage bottles. But this is also "not a sustainable solution," according to Emily Macintosh, textile policy expert for the European Environmental Bureau (EEB), a Brussels-based organization representing more than 170 environmental groups. Once the bottles are made into polyester fiber, hardly any of it goes on to be recycled again.

Despite polyester's shortcomings, Gregory Peters, a professor of environmental systems analysis, technology management, and economics at Sweden's Chalmers University of Technology, says recycled polyester textiles may still be the least-worst option. The environmental impact of microfibers may be less than other threats to ecosystems, such as the adverse effects of pesticides and land use required for the growing of cotton, he says.

"Meantime, polyester garments can demonstrate greater longevity than typical cellulosic garments," Peters says. "I would consider the most sustainable garments in my wardrobe to be those I can still use after 20 years because they prevent me from buying new clothes. They are made from polyester blends."

Given polyester's ubiquity, a growing number of companies are putting the microplastics problem aside and seeking to commercialize technologies for recycling polyester fiber. Typically, they feature a solvent step to remove cellulosic and other waste before polyester is depolymerized into ethylene glycol and terephthalic acid. This is followed by a purification step before repolymerization.

A small number of companies are already producing commercial volumes of recycled polyester fiber. They include Jeplan, which opened a polyester recycling plant in Japan in 2019 (see page 16).

The start-up Ambercycle (see page 14) is testing a recycling process at a pilot plant near Los Angeles that separates polyester from other fibers in mixed textile waste. Its process generates new polyethylene terephthalate pellets as well as polyester fiber. The firm claims that its technology uses 80% less energy than standard polyester recycling processes.

In January, the company raised $21.6 million in a funding round in which investor demand outstripped the number of shares Ambercycle had offered. Investors include H&M and the German fashion retailer Zalando.

CREDIT: RENEWCELL

Novel polyester recycling technologies are also emerging. Carol Lin, an associate professor in the School of Energy and Environment at the City University of Hong Kong, is developing a fermentation process in which waste cellulose fibers are converted into a sugar solution by an enzyme generated by a species of mold found on grapes. This enables the efficient separation of cellulosic fibers from polyester. The polyester can then go on to be made into new garments. H&M has been working with Lin on the project.

In its 2022 study, the EC asserts that recycling polyester and other synthetic materials is cost effective and easy to implement at a huge scale. It also found, however, that the addition of virgin material is required and that only a limited amount of recycled material will be present in the final fiber. Polyester fiber spinning is a delicate process that can be disrupted by the presence of even a small amount of incompatible polymer, the report says.

Like polyester, nylon 6 fibers can be recycled, in this case through depolymerization into the monomer caprolactam. Nylon garments also release microfibers during the wash cycle, but at one-sixth the level of polyester fibers, according to Textile Exchange.

As is the case with polyester, contamination of nylon 6 fibers can be a problem. Recycling firms require a minimum of 80% nylon content in the waste raw material, the EC says in its 2022 report. The characteristics of contaminants are important, as certain chemicals can significantly affect the nylon depolymerization reaction, according to the report.

Italy's Aquafil (see page 14) has been recycling nylon in commercial quantities for a number of years. The firm even takes nylon out of the oceans by collecting and recycling nylon fishing nets. It also uses old carpets and other textile scrap to make new fibers branded as Econyl. In early March, Aquafil formed a partnership with the salmon marketing council of Chile to collect and recycle old fishing nets in southern Chile, the world's third-largest producer of farmed salmon.

Regulation is coming

Even if technology firms develop processes that prove to be economically and environmentally viable, the textile industry should not be left to adopt them voluntarily, the EEB's Macintosh says. The EEB is advocating for regulation that would require textile companies to use more recycled fibers.

Such regulation is already on its way in Europe, where starting in 2025, clothing firms will be required to use a certain percentage of recycled content in their goods. Clothing producers are also beginning to design garments to make them easier to recycle, such as by avoiding the use of polyester thread in cotton clothes. H&M aims to design all its products for recycling by 2025.

Even within the constraints of regulation, Macintosh is skeptical that clothing companies will start to behave sustainably. "Consumers might put something in a box that says, 'We recycle your clothes.' But where does that go? How much of it actually ends up in textile-to-textile recycling?" she asks.

"Consumers might put something in a box that says, 'We recycle your clothes.' But where does that go?"

Clothing companies are creating collection points for the reuse or recycling of clothes, such as this box in a Zara store in London.

CREDIT: ALEX SCOTT/C&EN

EEB considers chemical recycling of fibers to be "obviously positive," Macintosh says. Nevertheless, "we are very wary that you can't recycle your way out of rampant overproduction," she says. "Above all, we are advocating for resource-use reduction in the first place."

Likewise, Textile Exchange asserts in its fiber market report that measures to reduce demand for clothing will be required alongside the chemical recycling of fibers if the textile industry is to turn around its environmental performance. "Using recycled fibers is very important. However, it is not enough. Investments in innovative business models and design for circularity are needed to decouple the industry from virgin material use and increase reuse rates," the group concludes.

Peters of Chalmers University points to another basic issue. "The fundamental problem is that garments are being made too cheaply, and even those that are robust are not being used for their potential life spans because the fast-fashion industry by definition sells newness," he says. "We need this to change through a concerted effort from industry and government to sell quality over quantity."

If the textile industry fails to make such fundamental changes to its business model, chemical recycling could simply add production capacity. "If recycling just increases the total supply of fiber, we are going backwards," Peters says. "The garment industry is already clinically obese—over-dimensioned for human needs—and should be made smaller for the planet's sake."

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We choose 20 promising companies making textiles more sustainable

» **Adriano di Marti**
» desserto.com.mx
» **Based:** Tesistán, Mexico
» **Launched:** 2019
» **Money raised in start-up funding rounds:** Not disclosed
» **Publicly traded:** No
» **Key partnerships:** Adidas, BMW, Fossil Group, H&M, Mercedes-Benz
» **Strategy:** Adriano di Marti uses nopal cactus, commonly called prickly pear, to make its leather alternative. The cacti need no irrigation beyond rainwater. The company makes the final product by mixing biobased oil additives with a resin made from cactus leaves, though it is working to increase the material's cactus-based content
» **Why watch:** Adriano di Marti partner BMW has announced its intention to stop using animal leather in its Mini and 5 Series vehicles.

» **AlgiKnit**
» algiknit.com
» **Based:** New York City
» **Launched:** 2017
» **Money raised in start-up funding rounds:** $20.1 million
» **Publicly traded:** No
» **Key partnerships:** Fashion for Good
» **Strategy:** AlgiKnit develops yarn from kelp. In contrast to textile materials that come from fossil fuels, this seaweed sequesters carbon dioxide. And unlike materials such as cotton, it does not require land or irrigation to grow. The yarn is designed to break down in landfills and composting facilities.
» **Why watch:** In December 2021, AlgiKnit announced the opening of a manufacturing hub in North Carolina.

» **Ambercycle**
» ambercycle.com
» **Based:** Los Angeles
» **Launched:** 2015
» **Money raised in start-up funding rounds:** $27 million
» **Publicly traded:** No
» **Key partnerships:** Avery Dennison, Come Back as a Flower, EigenDraads
» **Strategy:** Ambercycle regenerates polyester from textile waste, including blended fabrics (see page 12). The company's chemical recycling method does not melt or degrade fibers, so the recovered polyester is comparable to virgin material and can be used repeatedly. Ambercycle's partners recycle cellulosic materials, such as the cotton in fabric blends.
» **Why watch:** In December 2021, the company's regenerated polyester, called cycora, appeared in a pair of embellished pants by fast-fashion retailer H&M.

» **AMSilk**
» amsilk.com
» **Based:** Planegg, Germany
» **Launched:** 2008
» **Money raised in start-up funding rounds:** $42 million
» **Publicly traded:** No
» **Key partnerships:** Adidas, Airbus, Mercedes-Benz
» **Strategy:** AMSilk makes synthetic spider silk fibers via Escherichia coli fermentation and without any petroleum feedstocks. The company says its biodegradable fibers can be woven into fabric with standard textile manufacturing equipment (see page 6).
» **Why watch:** Mercedes-Benz unveiled a concept car in January 2022 with synthetic silk straps that close the vehicle doors.

» **Aquafil**
» aquafil.com
» **Based:** Arco, Italy
» **Launched:** 1965
» **Money raised in start-up funding rounds:** $171 million
» **Publicly traded:** Yes, IPO 2017
» **Key partnerships:** Atando Cabos, Flor, Itochu, Tarkett
» **Strategy:** Aquafil, a longtime manufacturer of nylon fibers, recycles nylon 6 from sources such as old

carpets and abandoned fishing nets. After breaking the nylon 6 down to its molecular building block, caprolactam, and removing impurities, the firm produces yarns that it says equal the performance of never-before-used nylon 6 (see page 13).
» **Why watch:** Aquafil has partnered with the engineered microbe fermentation company Genomatica to make caprolactam from sugar rather than synthetic feedstocks.

» **BlockTexx**
» [blocktexx.com]
» **Based:** Loganholme, Australia
» **Launched:** 2018
» **Money raised in start-up funding rounds:** $3.4 million
» **Publicly traded:** No
» **Key partnerships:** Star Entertainment, Wiley
» **Strategy:** BlockTexx's chemical separation of textile fibers reclaims the raw materials of polyethylene terephthalate and cellulose from polyester and cotton, respectively. The company envisions implementing the digital ledger known as blockchain to track textile waste and its reclaimed materials in a circular economy.
» **Why watch:** BlockTexx was a winner in the 2021 Australian Technologies Competition, a nationwide contest and networking platform for start-ups. The firm is building a textile recycling plant at a site in Logan, Queensland, Australia.

» **Circ**
» [circ.earth]
» **Based:** Danville, Virginia
» **Launched:** 2011
» **Money raised in start-up funding rounds:** $15.5 million
» **Publicly traded:** No
» **Key partnerships:** Andritz, Fashion for Good, Marubeni, Patagonia
» **Strategy:** Circ, formerly Tyton BioSciences, extracts cellulose and depolymerizes polyester in blended fabrics with supercritical water—water heated above its boiling point while under pressure (see page 6).
» **Why watch:** Circ says its process can handle small amounts of spandex in clothing. Spandex is among the most difficult textile materials to recycle.

» **Circular Systems**
» [circularsystems.com]
» **Based:** Los Angeles
» **Launched:** 2017
» **Money raised in start-up funding rounds:** $9.1 million
» **Publicly traded:** No
» **Key partnerships:** Converse, Madewell, Nike
» **Strategy:** Circular Systems' Agraloop platform purifies crop waste like pineapple leaves and hemp stalks into cellulose fibers. The company also says it has technology to recycle cotton and to create performance materials that dry quickly, wick sweat, and shed minimal fibers—all without synthetic chemical finishes.
» **Why watch:** In December 2021, Circular announced a deal with Nishat Mills, one of Pakistan's largest textile companies and a supplier to multiple global brands, to increase production of its sustainable fibers in South Asia.

» **Colorifix**
» [colorifix.com]
» **Based:** Norwich, England
» **Launched:** 2016
» **Money raised in start-up funding rounds:** $31.8 million
» **Publicly traded:** No
» **Key partnerships:** Forster Rohner, H&M, Tintex
» **Strategy:** Colorifix genetically engineers microbes to produce pigments created in nature. The most stable of the pigments can be used instead of conventional dyes to color fabrics. To deposit the pigments permanently, the technology bursts the microbes open, whereupon salts and metal ions in the microbes' cytoplasm rather than harsh chemicals act as fixing agents.
» **Why watch:** In December 2021, Colorifix debuted tracksuits in two colors in collaboration with sustainable-fashion brand Pangaia.

» **DyeCoo Textile Systems**
» [dyecoo.com]
» **Based:** Weesp, the Netherlands
» **Launched:** 2008
» **Money raised in start-up funding rounds:** $6.5 million
» **Publicly traded:** No
» **Key partnerships:** Adidas, Archroma, DuPont Biomaterials, Huntsman, Nike
» **Strategy:** DyeCoo uses supercritical CO_2 to deposit vibrant colors without any wastewater. The company says its machines recycle 95% of the CO_2 used during dyeing.
» **Why watch:** DyeCoo has sold at least 15 machines to dyeing houses in Taiwan, Thailand, and Vietnam. The company has planned projects in Bangladesh, the European Union, India, South Korea, and Turkey.

» **Infinited Fiber**
» [infinitedfiber.com]
» **Based:** Espoo, Finland
» **Launched:** 2016
» **Money raised in start-up funding rounds:** $52.3 million
» **Publicly traded:** No
» **Key partnerships:** AFRY, Circular Fashion Partnership, Inditex, Patagonia, Wrangler
» **Strategy:** Infinited Fiber mechanically disintegrates waste rich in cellulose, such as old cotton cloth, used cardboard, and leftover wheat stalks. Further treating the waste with urea yields cellulose carbamate fibers, which the company says feel like cotton (see page 11).
» **Why watch:** Infinited runs pilot plants in Finland that make 150 metric tons (t) of its fiber annually, and the company expects to open a plant in 2024 capable of making 30,000 t annually. Infinited expects a steady stream of raw material from the European Union starting in 2025, when mandated collection of waste textiles begins.

Jeplan
jeplan.co.jp/en
Based: Tokyo
Launched: 2007
Money raised in start-up funding rounds: $17.7 million
Publicly traded: No
Key partnerships: Muji, Patagonia, The North Face
Strategy: Jeplan, one of the Companies to Watch in the Q1 2020 Discovery Report, depolymerizes polyester fibers with glycol compounds and a catalyst to make the monomer bis(2-hydroxyethyl) terephthalate. The monomer can then be used to manufacture new textiles. The company, which removes impurities with crystallization and distillation, says its product is the same quality as material made from petroleum.
Why watch: Jeplan opened a polyester recycling plant in Japan in 2019.

Kintra
kintrafibers.com
Based: New York City
Launched: 2018
Money raised in start-up funding rounds: $2 million
Publicly traded: No
Key partnerships: Pangaia
Strategy: Kintra sources corn- and wheat-derived sugars to make polybutylene succinate resins and fibers. The materials have stretch and moisture-wicking properties like petroleum-derived polyester, nylon, or spandex, while also being biodegradable in industrial composting facilities.
Why watch: The company says that, unlike other synthetic textiles, its biodegradable products do not pollute bodies of water with microfibers.

Natural Fiber Welding
naturalfiberwelding.com
Based: Peoria, Illinois
Launched: 2015
Money raised in start-up funding rounds: $155.6 million
Publicly traded: No
Key partnerships: Allbirds, Motherson, Porsche, Ralph Lauren
Strategy: One of C&EN's 2021 10 Start-Ups to Watch, Natural Fiber Welding uses ionic liquids to unravel and then enmesh yarns from materials such as cotton, hemp, or wool, creating longer and stronger threads than in other recycled textiles. The company also offers a recyclable and biodegradable leather alternative made from agricultural waste and other plant-based feedstocks.
Why watch: Natural Fiber plans to release data later in 2022 from the first life cycle assessment of its products' environmental impact.

Renewcell
renewcell.com
Based: Stockholm
Launched: 2012
Money raised in start-up funding rounds: $10.6 million
Publicly traded: Yes, IPO 2020
Key partnerships: Birla Cellulose, Daiwabo Rayon, Levi's, Tangshan Sanyou
Strategy: Renewcell converts cellulose-rich textile waste such as cotton fabric into a slurry or pulp, which can be dried into sheets for transport to fiber and yarn makers (see page 10). The process is similar to how viscose is made from wood pulp.
Why watch: In December 2021, Renewcell signed agreements with three European textile sorters, each in a different country, that will supply thousands of metric tons of waste fabrics to its forthcoming recycling plant in Sweden.

Resortecs, Recycling made Easy.

Resortecs
resortecs.com
Based: Brussels
Launched: 2017
Money raised in start-up funding rounds: $2.2 million
Publicly traded: No
Key partnerships: H&M
Strategy: Resortecs offers heat-dissolvable stitching thread with different melting points to ease disassembly of clothing for recycling. The company says dismantling clothes in its commercial ovens reduces textile waste, water usage, and CO_2 emissions compared with traditional disassembly and recycling.
Why watch: In December 2021, Resortecs demonstrated a prototype oven that can process 1 t of textiles per day. It plans to launch a system in 2022 that can handle 13 t daily.

SeaChange Technologies
seachangetechnologies.com
Based: Raleigh, North Carolina
Launched: 2014
Money raised in start-up funding rounds: Not disclosed
Publicly traded: No
Key partnerships: Arvind, Fashion for Good
Strategy: SeaChange Technologies purifies water contaminated with dyes and other chemicals commonly used by the apparel industry. Rather than employ specialized filters or membranes, its process converts water to an aerosol and then creates a tornado-like effect inside a specialized instrument that draws away contaminants.
Why watch: Last year, SeaChange received funding from a US government initiative focused on energy efficiency in manufacturing. With multiple collaborators, the company will undertake a project to recycle polyester blends with zero waste.

» **Spiber**
» spiber.inc/en
» **Based:** Tsuruoka, Japan
» **Launched:** 2007
» **Money raised in start-up funding rounds:** $910 million
» **Publicly traded:** No
» **Key partnerships:** ADM, The North Face
» **Strategy:** Spiber incorporates optimized spider silk genetic sequences into microorganisms and uses plant feedstocks to ferment a synthetic material with strength, elasticity, and softness akin to a spider's own silk. The company says its brewed protein textiles are biodegradable in soil and water.
» **Why watch:** Spiber's first industrial-scale plant, in Thailand, is scheduled to open in 2022, with a second in the US in 2023.

» **Stony Creek Colors**
» stonycreekcolors.com
» **Based:** Springfield, Tennessee
» **Launched:** 2012
» **Money raised in start-up funding rounds:** $15.8 million
» **Publicly traded:** No
» **Key partnerships:** Donald Danforth Plant Science Center, J.Crew, Lucky Brand
» **Strategy:** Stony Creek Colors produces plant-based dyes—with a focus on indigo—for textiles. Indigo, whether natural or petroleum-derived, must be chemically reduced to be water soluble for dyeing. Instead of a synthetic reducing agent, the company's process uses green hydrogen made via water electrolysis.
» **Why watch:** In April, Stony Creek expanded its deal with dye and pigment maker Archroma, which will test the plant-based dyes with denim companies.

» **Worn Again Technologies**
» wornagain.co.uk
» **Based:** Nottingham, England
» **Launched:** 2005
» **Money raised in start-up funding rounds:** $15.5 million
» **Publicly traded:** No
» **Key partnerships:** ASICS Europe, H&M, Kering, Sulzer
» **Strategy:** Worn Again Technologies separates, decontaminates, and extracts polyethylene terephthalate and cellulose from blended polyester and cotton waste textiles.
» **Why watch:** Worn Again opened a pilot plant in 2020 to boost production and in January 2022 announced its intention to build a full-scale plant.

Note: Companies were included because of the novelty and potential of their methods, amount of capital raised, number of partnerships, and number and identity of investors.

Sources: Crunchbase (accessed June 2022), company websites, news reports.

Evrnu: Turning old clothes into new fabrics

GINA VITALE, C&EN STAFF

There comes a day when you must part ways with your beloved old Pink Floyd T-shirt—splattered with paint, perpetually wrinkled, and too torn to be worn outside on a chilly day. Into the trash it goes, right?

Wrong. Or at least it could be, according to the founders of Evrnu, a start-up looking to use its technology to give textiles a second life—and a third and a fourth.

Christopher Stanev (left) and Stacy Flynn, founders of Evrnu

Stacy Flynn, Evrnu's CEO and cofounder, spent much of her career in the garment industry, working as a global textile specialist for companies like DuPont and Eddie Bauer. Several years ago on a trip to an area of China concentrated with textile subcontractors, she and a colleague realized they couldn't see each other's faces through the smog. Pollution from the textile process clogged the air and blackened the water.

"I came out of that 1-month trip thinking that this cannot be how the story ends," Flynn says.

Later, when working as a fabric specialist for Target, Flynn met Christopher Stanev, now the president and cofounder of Evrnu. Stanev had spent many years working in textile engineering and would later hold technical leadership positions at companies like Nike and Gloria Jeans. They dreamed up and started Evrnu, a company that creates and licenses technologies to allow textiles to be continually recycled rather than tossed into landfill.

Evrnu developed its first technology in-house and launched it in 2019. Called NuCycl, it's a recycling process in which cotton garments are stripped of dyes, prints, and other adornments, leaving behind only cellulose. The cellulose is purified and activated into a pulp that is ready to be dissolved in a solvent. Once the pulp is liquefied, cellulose-based fibers can be extruded from it and used to make new fabric.

Evrnu has licensed NuCycl technology to brands like Adidas. It's working on further innovating the solvent in which the cellulose is dissolved to produce fibers. The firm says it is using "a blend of different solvents and catalysts" that can dissolve longer molecules, allowing the polymer chains to maintain their integrity through multiple cycles of reuse. The company is also looking to expand its textile recycling technology to materials other than cotton.

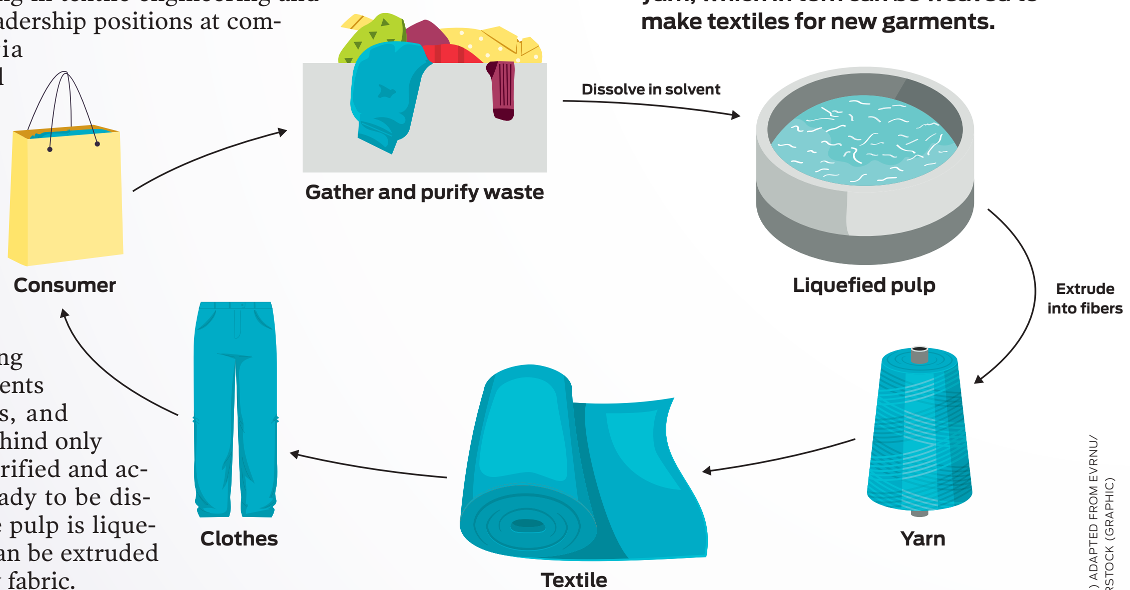
Evrnu at a glance

- **Launched:** 2014
- **Based:** Seattle
- **Strategy:** Repolymerization of textile waste into premium materials
- **Funding or notable partners:** $31 million in start-up funding rounds; brand partners include Adidas, Levi Strauss, Stella McCartney, and Target

SOURCES: COMPANY WEBSITE, CRUNCHBASE.

Nu life for old clothes

Evrnu's patented NuCycl technology allows cotton waste to be dissolved and extruded into cellulose fibers. Those fibers can then be respun into yarn, which in turn can be weaved to make textiles for new garments.



CREDIT: EVRNU (FOUNDERS) ADAPTED FROM EVRNU/ YANG H. KU/C&EN/SHUTTERSTOCK (GRAPHIC)

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HOT SHEET

Recyclable fabric from polyethylene

BETHANY HALFORD, C&EN STAFF

Polyethylene fabric is comfortable and recyclable.

CREDIT: SVETLANA V. BORISKINA

Today's plastic grocery bag could be tomorrow's high-tech tracksuit, thanks to fabric made from polyethylene—the same polymer used to make plastic wrap. Analyses suggest that the fabric could be more sustainable than conventional fabrics, including cotton and polyester. Polyethylene fibers take less energy to produce than those fabrics, and they resist stains and dry quickly.

Svetlana V. Boriskina, a scientist at the Massachusetts Institute of Technology, led the group that developed the polyethylene textiles. She says she was originally attracted to the polymer because it allows infrared radiation, or heat, to escape from the body, cooling the wearer. But textile experts were skeptical that polyethylene—a material known for blocking moisture—would make for a comfortable fabric.

Boriskina and coworkers found that they could use standard textile industry equipment to make polyethylene fibers and yarns and then knit or weave them into fabric (*Nat. Sustain.* 2021, DOI: 10.1038/s41893-021-00688-5). The extrusion process to make the fibers oxidizes the polyethylene on the surface of the fibers, which gives them moisture-wicking properties. Because the inside of the fibers is hydrophobic, the moisture doesn't seep in but instead evaporates very quickly. "This is what sets it apart from other wicking materials like cotton," Boriskina says. YuHuang Wang, an expert in synthetic materials at the University of Maryland, who was not involved in the project, says it's surprising that polyethylene can be moisture wicking and adds that the work is an important step toward using polyethylene as a recyclable textile.

The extruded polyethylene fibers feel soft, silky, and cool to touch, Boriskina says. But they can be engineered to feel like cotton or fleece. The white fibers can be dyed using an environmentally friendly process in which a coloring agent is added during extrusion.

While the recyclable material won't be in any ready-to-wear collections next season, Boriskina says MIT spun out a start-up, Neramco, in 2020 to create the fabric, which is called Svetex. She's working with the US Army, NASA, and athletic clothing makers on applications for the material.

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HOT SHEET

Chemistry in Pictures: 'Unleather' factory

CRAIG BETTENHAUSEN, C&EN STAFF

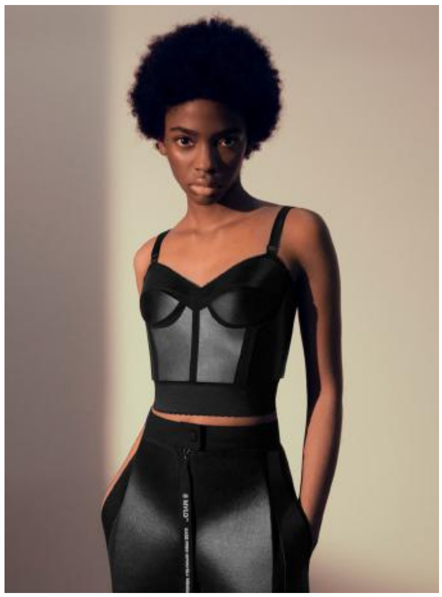
The tufts of white fluff in the factory photo above will soon undergo a stark transformation into the black, leather-like material adorning this model, or this duffel bag. The trays are full of mycelium, the root structure of mushrooms, which the next-generation materials company Bolt Threads—one of C&EN's 2015 10 Start-Ups to Watch—is growing on sawdust under carefully controlled conditions. Bolt is collaborating with several backers of its Mylo material, including fashion designer Stella McCartney and athleisure powerhouse Lululemon, to give vegetarians and vegans new high-end sartorial options. The McCartney bustier and trousers are not for sale, and as of this report's deadline, lululemon bags with handles and zipper pulls made from Mylo "unleather" are sold out online and at retail locations. Readers may recognize Bolt from its work on spider silk expressed in yeast cells. For now, Bolt CEO Dan Widmair is working hard on scaling up Mylo. Bolt aims to increase its Mylo mushroom leather to 93,000 m^2 annually by the end of 2022. And Widmair says he has several more biobased materials innovations literally in the freezer.

To read more about Mylo and other leather alternatives making their way to the market, check out C&EN's 2021 feature story here.

Bolt Threads at a glance

» **Launched:** 2009
» **Based:** Emeryville, California
» **Strategy:** Sustainable synthetic silk and vegan leather
» **Funding or notable partners:** $471.1 million in start-up funding rounds; brand partners include Adidas, French luxury group Kering, Lululemon, and Stella McCartney

SOURCES: COMPANY WEBSITE, CRUNCHBASE.



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CREDIT: BOLT THREADS (MATERIAL); COURTESY OF BOLT THREADS/STELLA MCCARTNEY (MODEL); LULEMON (DUFFLE BAG)

READING LIST

Our picks of the patent and journal literature on sustainable textiles

2022

» AMSilk. **"Methods for Producing High Toughness Silk Fibres."** US Patent 11,248,120, filed Sept. 10, 2018, and issued Feb. 15, 2022.

2021

» Stony Creek Colors. **"Dyed Fibers and Methods of Dyeing Using O,O′-Diacetyl Leucoindigo."** US Patent 11,208,760, filed Dec. 6, 2018, and issued Dec. 28, 2021.

» Vandelook, Simon, Elise Elsacker, Aurélie Van Wylick, Lars De Laet, and Eveline Peeters. **"Current State and Future Prospects of Pure Mycelium Materials."** *Fungal Biol. Biotechnol.* 8 (Dec. 20, 2021): 20. https://doi.org/10.1186/s40694-021-00128-1.

» Jönsson, Christina, Ren Wei, Antonino Biundo, Johan Landberg, Lisa Schwarz Bour, Fabio Pezzotti, Andreea Toca, Les M. Jacques, Uwe T. Bornscheuer, and Per-Olof Syrén. **"Biocatalysis in the Recycling Landscape for Synthetic Polymers and Plastics towards Circular Textiles."** *ChemSusChem* 14, no. 19 (Oct. 5, 2021): 4028–40. https://doi.org/10.1002/cssc.202002666.

» Colorifix. **"Method of Dyeing Fabric Using Microorganisms."** US Patent 11,105,041, filed Nov. 22, 2019, and issued Aug. 31, 2021.

» Bolt Threads. **"Composite Material, and Methods for Production Thereof."** US Patent 11,015,059, filed July 30, 2020, and issued May 25, 2021.

» Guo, Zengwei, Erik Adolfsson, and Pui LamTam. **"Nanostructured Micro Particles as a Low-Cost and Sustainable Catalyst in the Recycling of PET Fiber Waste by the Glycolysis Method."** *Waste Manage.* 126 (May 1, 2021): 559–66. https://doi.org/10.1016/j.wasman.2021.03.049.

» Natural Fiber Welding. **"Methods, Processes, and Apparatuses for Producing Welded Substrates."** US Patent 10,982,381, filed March 27, 2017, and issued April 20, 2021.

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Note: This list was chosen by experts who work in the field, CAS information scientists, and C&EN editorial staff.


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