SUSTAINABILITY

Transforming textiles

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

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 of them 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

In brief

New technologies for chemically recycling textile fibers are emerging around the world. They have the potential to substantially reduce the textile industry's huge environmental footprint. Consumers could soon be wearing brand-new clothes made from garments that otherwise would have ended up in a landfill or incinerator. But the technologies are far from mature. And industry watchers warn that if the textile industry is to become truly sustainable, a move away from fast fashion is also necessary.

CREDIT: MIKE REDDY

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.

Renewcell creates a dissolving pulp from waste cotton that forms the basis for new cellulosic 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. By 2030, textile waste will rise to 134 million t, the foundation predicts.

Existing technologies and systems are not solving the problem. Mechanical 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. Ultimately, such activity, along with the reuse of clothing, 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 clothes 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

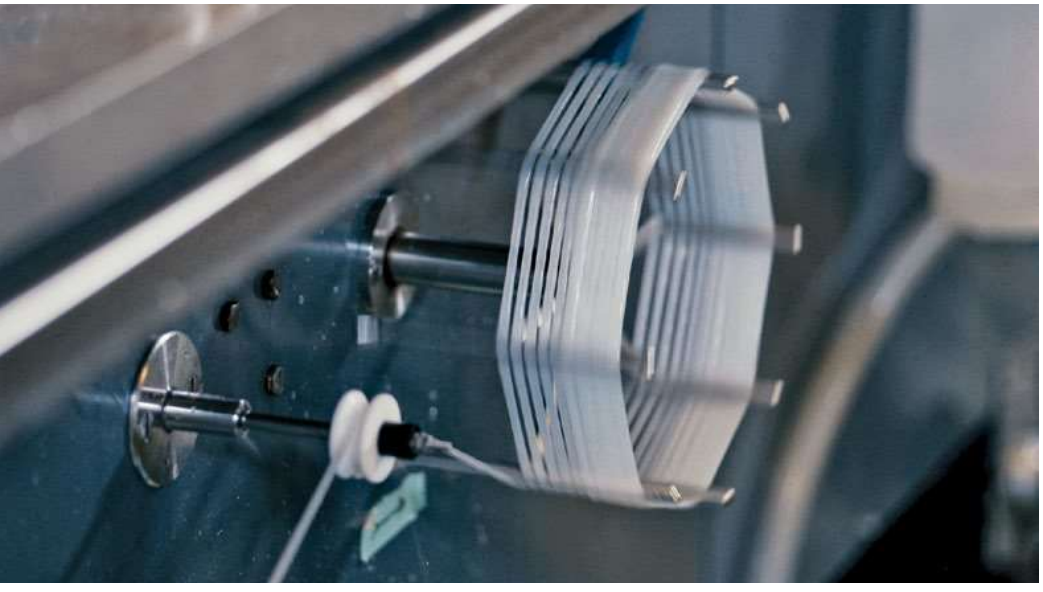
Clothing companies working with GFA are also funding chemical recycling technology start-ups. H&M, for example, has invested in Renewcell, one of more than a dozen companies that are developing cellulose recycling technologies in Scandinavia and neighboring Finland.

Many firms in this far north region of Europe were spun out of universities that have long researched cellulosic chemistry as a result of being located near producers of pulp and paper. Universities that have spun out waste textile recycling technology include Aalto University in Finland and KTH Royal Institute of Technology in Sweden.

Renewcell's Circulose process 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 then 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

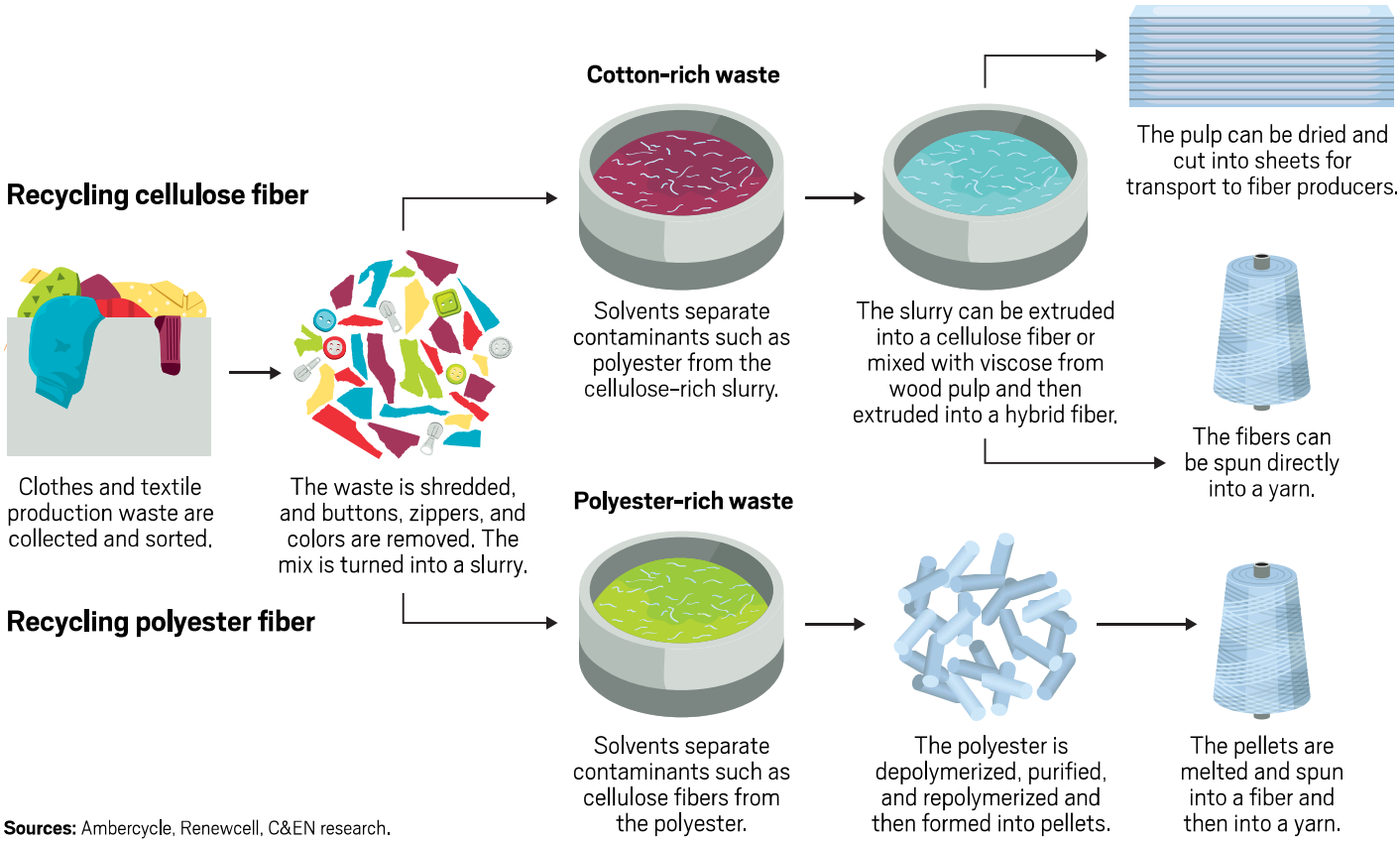
Nordic Bioproducts produces fiber from its viscose-type pulp process.



CREDIT: RENEWCELL (DENIM PULP); NORDIC BIOPRODUCTS (PRODUCTION)

Old clothes to new fibers

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



Sources: Ambercycle, Renewcell, C&EN research.

CREDIT: YANG H. KU/C&EN/SHUTTERSTOCK (GRAPHIC); YANG H. KU/C&EN (T-SHIRT)

wood pulp or run it at 100%," says Kristina Elg Christoffersson, Renewcell's chief technology officer.

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, in the second quarter of 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. 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 then 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.

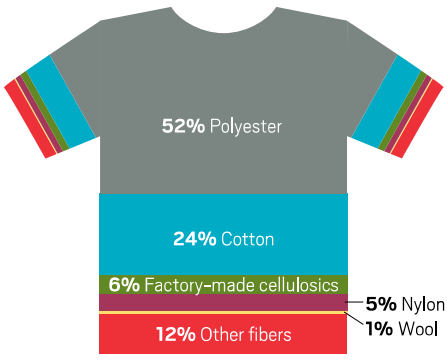
"This is technically and chemically quite a simple process," says Sakari Siren, Infinited's chief technology officer.

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 and Levi Strauss. It plans to increase production to 60,000 t per year of a fiber blend with a 30% concentration

The market

Polyester is the dominant fiber in the global textile industry.



Market size in 2020 = 109 million metric tons

Source: Textile Exchange.

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

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. Circ, which is a partner with the clothing firm Patagonia and the fashion industry initiative Fashion for Good, claims its process can be run on fiber blends and that the level of its recovery of fibers is more than most other separation techniques.

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 Lenzing's circularity initiative. The Austrian firm indicates that it will be sourcing postconsumer waste textiles from Europe, while it may get postindustrial waste—scraps of textile waste left over 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 need for funding

While they iron out their technological wrinkles, companies recycling cellulosic fiber are seeking funding to commercialize their nascent processes. Securing this cash is not a given in the current economic climate.

"There is very little funding for expansion of science and technology in the textile-apparel-fashion industry," says Stacy Flynn, CEO and cofounder of Seattle-based Evrnu, which is developing a viscose-type cellulosic waste recycling technology and was one of C&EN's 10 Start-Ups to Watch in 2020.

Evrnu has raised $20 million to date from investors, but this is not enough for the firm to deploy its NuCycl process at scale. "We will need multiyear volume commitments from brand retail partners so capital can be secured to design capacity efficiently," says Flynn, a former textile specialist for DuPont.

Evrnu's process has a very small environmental footprint, Flynn says. Each metric ton of waste-derived pulp generated by the firm's process has a carbon footprint of about 1 t of carbon dioxide equivalent, which is about one-tenth that of viscose fiber derived from virgin wood pulp, she says.

Despite the potential of technologies such as NuCycl to reduce the textile sector's environmental footprint, buy-in from companies in the textile supply chain remains modest. Textile companies have yet to fully quantify the impact of recycling, "so the inertia in big businesses to stick to their current model is quite great," Flynn says. "That said, consumer demand from a

"If recycling just increases the total supply of fiber, we are going backwards."

—Gregory Peters, professor, Chalmers University of Technology

CREDIT: RENEWCELL

Evrnu partnered with Adidas and Stella McCartney to make a hoodie from waste cotton using its NuCycl process.

social responsibility standpoint is surging."

Companies such as H&M and Ikea say they are responding to such consumers. H&M states that it will start using 100% recycled or other sustainably sourced materials by 2030. Ikea says it will use only renewable or recycled materials by 2030 and that as part of its strategy, it will replace virgin polyester with recycled polyester. The EC, in its 2021 study, forecasts that demand for recycled textiles will take off and that the 10 largest chemical recycling firms around the world will be collectively recycling about 900,000 t per year of textiles by 2025.

GFA is optimistic that recycled fibers will be able to compete with virgin fibers on price once they are being produced at this scale. An analysis by the group and the consulting firm McKinsey shows that "by making new fibers from old, clothing retains its greatest financial value. Cost parity can be achieved," GFA's Syrett says. "Announcements of investment in recycling factories are being made. Scale-up of chemical recycling technologies is really starting to happen now."

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 are from synthetic textiles and that most of this fraction is polyester.

While almost no polyester fiber-to-fiber recycling is taking place around the world, 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.

The start-up Ambercycle 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 its technology uses 80% less energy than standard polyester recycling processes.

Clothing companies such as Mango say they are committed to the use of chemically recycled fibers.

CREDIT: EVRNU (HOODIE); ALEX SCOTT/C&EN (MANGO SIGN)

“It does not make sense to transport postconsumer waste around the globe.”

—**Sonja Zak,** head of circularity initiative, Lenzing

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.

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 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. Earlier this month, 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.

Polyethylene, a material vilified for its use to make single-use plastic bags, could also be recycled into fibers for clothes and other textiles, according to Svetlana V. Boriskina, a scientist at the Massachusetts Institute of Technology. Polyethylene fibers take less energy to make than cotton or polyester fibers, and their chemistry makes them stain resistant and quick to dry, Boriskina found.

Since Boriskina and her colleagues published their findings in 2021, they have created a company, Neramco, to commercialize their technology.

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 starting 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.

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.” ■

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