DISCOVERY REPORT

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The future of plastic

The world has a plastic pollution problem. We examine the chemistry it will take to close the loop on plastics recycling and turn an environmental scourge into a source of raw materials

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The future of plastic

Imagining a modern grocery store, hospital, or laboratory without plastic is practically an impossibility. Yet the sheer magnitude of the plastic waste problem has at least some segments of the public entertaining the idea.

Plastic is everywhere because few materials match its versatility. Glass, aluminum, and cardboard are single products with comparatively limited applications. When it comes to reuse, however, the homogeneity of those materials is advantageous. According to 2017 data from the Environmental Protection Agency, the US recycled just 8.4% of the 32 billion kg of plastic that consumers threw away. That pales in comparison to the recycling rates for glass (26.6%), metal (33.3%), and paper (65.9%). And the trend in recent years is discouraging; the US's plastic recycling rate in 2015 was 9.1%. If chemistry helped get the world into this mess, surely it can help get us out. But what developing strategies could complement traditional recycling? And what roadblocks stand in the way of scaling them?

This Discovery Report delves into chemical recycling technologies. Contributing editor Carmen Drahl, who has covered organic chemistry and green chemistry for C&EN, edited the report. It includes a reading list of papers and patents curated by our sources as well as researchers at the CAS division of the American Chemical Society.

Inside, you'll hear from heavy hitters in the packaging industry, experts in depolymerization and pyrolysis, the scientists sounding the alarm about plastics' impact on our ecosystems, and many more.

As an ACS member, you get exclusive access to the Discovery Report, a quarterly publication analyzing the new science and technology defining the chemical sciences and our industry. Look for your next one in the second quarter of 2020.

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INSIDE

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CHEAT SHEET

5 questions and answers about what's next for plastics recycling

Q. What happens to plastic after the recycling bin?

» **Even if a plastic product has a recycling symbol on it,** putting it in a curbside bin doesn't guarantee it will have another useful life.

» **Recycling facilities select only the highest-value plastics to process.** Plastics may or may not be recycled depending on resin type (indicated by a recycling symbol) or product type. Mixed plastics and multilayered products are difficult to recycle.

» **Most centers recycle plastic mechanically** by washing it and melting it for reuse. The process doesn't handle contamination such as mayonnaise or grime well.

» **Recycled plastics usually end up** in lower-value products than their virgin plastic counterparts.

Q. Are there alternatives to traditional recycling?

» **Chemical recycling methods** might prove a complement to mechanical recycling.

» **Depolymerization uses chemical or biological** catalysts to break plastic polymers down to their monomer building blocks, which could be converted into recycled products without compromising performance.

» **Pyrolysis, which occurs under low-oxygen conditions** and temperatures of 400 °C or above, cracks long polymer chains into shorter hydrocarbons, which can be used in fuels, petrochemicals, or new plastics.

» **A handful of firms are exploring yet other techniques,** including using biobased solvents to dissolve and purify postconsumer polystyrene, a material that is notoriously tough to recycle.

Q. Why are plastics makers interested in chemical recycling?

» **Documentaries about the effects of plastic pollution** on sea life and the scourge of microplastics have led the public to demand solutions to the plastic waste problem.

» **Governments have taken action** to change the plastic status quo. For example, China has limited imports of foreign plastic waste, and US cities have banned straws and plastic bags.

» **Compared with mechanical recycling,** chemical recycling technology is not as hampered by contamination, and therefore it could handle greater percentages of incoming plastic waste.

» **Brands are loath to compromise on performance,** and chemical recycling offers the potential to make a recycled product of equal caliber to virgin plastic.

Q. What are some obstacles to chemical recycling?

» **To have a shot at profitability,** recyclers must aggregate large amounts of plastic waste and invest in large, costly plants.

» **Municipalities have little incentive** to try recovering value from waste plastic, as the fees they pay to send plastic trash to the landfill are typically low.

» **The prices of virgin plastic resins are driven by** the price of oil, and they tend to be inexpensive compared with recycled materials.

Q. What does the future hold for plastic recycling?

» **No one strategy can solve the gargantuan plastic waste problem.** Recycling technology should complement efforts to develop biodegradable plastics and intrinsically recyclable polymers, as well as grassroots efforts to reduce plastic consumption.

» **Opportunities lie with plastics that are rarely recycled in the US,** such as polyvinyl chloride (PVC). Europe's VinylPlus recycling program for PVC could become a global model.

» **Some 250 firms, including PepsiCo, Unilever, and H&M,** have pledged to boost packaging's recycled and reusable content, as well as to reduce packaging. Public reports on their progress will highlight new challenges for the chemistry community to address.

FROM THE FRONT LINES

8 experts on plastic waste and recycling share their visions for solutions

Marco Castaldi

» **Professor, City University of New York**

Marco Castaldi believes that plastic and efforts to ban it aren't going anywhere. Plastic is too useful a material, and the public, while more aware of downsides, prioritizes convenience. Recycling has its place but is hard to implement and does not always work, with the result that most plastic waste goes to landfills.

Instead, as plastic waste volumes rise worldwide, municipalities need to look more seriously at converting plastics into energy, chemicals, or fuels. "For materials that you cannot recycle technically or because there's no market, the next best step is to recover their energy for reducing the overall environmental impact," Castaldi says. "Decomposing it slowly in landfills is not the way to go."

Castaldi and his team sifted through reams of publicly available data to analyze waste management in New York City and found that only half of the plastic that residents sort for recycling actually gets recycled. "That's not counting the plastics that didn't even make it to the blue bin," he says. The problem is worse in developing countries that lack proper waste management.

Nonrecycled plastics can be converted into synthetic liquid fuels via pyrolysis, which involves heating them in an oxygen-free environment to transform them. Even if the fuel isn't of suitable quality for cars, Castaldi says, it's still valuable for residential and commercial heating.

"We're investing in material that companies want but can't figure out how to use … making sure they're creating solutions instead of problems."

Bridget Croke

» **Managing director, Closed Loop Partners**

Consumer and retail giants are pledging to reduce plastic use and increase recycled content in packaging. Bridget Croke is helping them follow through. Her New York–based investment firm channels venture capital and private equity to sustainability start-ups, plastic collection and processing infrastructure, and recycling innovations "so we can transfer as much plastic as possible back into the supply chain," Croke says. "We're investing in material that companies want but can't figure out how to use . . . making sure they're creating solutions instead of problems."

For example, with private equity funding from institutional investors, Closed Loop Partners recently became the majority owner of Balcones Resources' plastic collection and recycling facility in Texas. The goal is to improve and scale recycling so that large beverage companies get the high-quality recycled materials they need.

Closed Loop has also brought together retail brands and manufacturers, chemical companies, and experts from environmental organizations to facilitate accelerating chemical recycling technologies to market.

It's critical to help consumer goods companies "think more creatively about procurement practices and new delivery models," Croke says. Case in point: her firm's investment in the Chilean start-up Algramo, which provides mobile units for consumers to refill dish soap and detergent. Closed Loop is helping Algramo establish itself in North America and connect it with big-brand partners.

Ricardo Cuetos

» **Vice president Americas, Ineos Styrolution America**

The main problem with polystyrene is its perception, according to Ricar-

CREDIT: ALL IMAGES COURTESY OF INSTITUTIONS do Cuetos. His company's styrenics find use far beyond much-maligned food-service packaging. The material fills critical needs in the automotive, construction, and health-care industries, he says. And the material is now perfectly recyclable thanks to new chemical technologies (see page 18). "It's the only polymer we can get back to its building block monomer, styrene, that is the same as virgin styrene," Cuetos says.

Collecting the light, bulky, and breakable material is not cost effective, which explains polystyrene's abysmal recycling rates. Increasing the value of used polystyrene will change that, Cuetos says.

Through recent joint agreements with chemical recycling companies Agilyx, GreenMantra Technologies, and Pyrowave, Ineos aims to collect and recycle all forms of polystyrene waste—rigid, flexible, or foam—throughout the Midwest and turn it into styrene that the company will process and turn back into new polystyrene for various uses. The recycled material could be expensive in the beginning, depending on the process and scale, but "we're aiming to make it a sustainable solution," Cuetos says. "Our target is to recycle 100% of polystyrene going to landfill."

Banning polystyrene is not an answer, he says. "We need to agree to use less, use wisely, and find the best solution for its end of life. The chemical recycling technology didn't exist a couple years ago, but now it does, and, we will have to make it a reality."

"Our target is to recycle 100% of polystyrene going to landfill."

Conrad MacKerron

» **Senior vice president, As You Sow**

Conrad MacKerron's mission is to get companies to take more responsibility for the waste they generate. For over 20 years, he has engaged with beverage, fast-food, and consumer goods giants to adopt policies that reduce plastic use, make packaging recyclable, and cover some of the cost of waste collection.

Companies bear the responsibility because of their economic power and marketing influence, MacKerron says. "They created the wasteful consumer culture of the takeout container that's tossed and sits 400 years in a landfill," he says. The economic argument, according to his nonprofit's research, is that $12 billion worth of recyclables go to landfills every year.

As You Sow has launched an alliance of 40 investors to talk with companies that produce or use high volumes of plastic packaging. These dialogues have led to McDonald's and Dunkin' agreeing to eliminate rarely recycled polystyrene foam cups and Starbucks agreeing to phase out single-use cups. The Berkeley, California–based nonprofit was also a force behind PepsiCo and Unilever's public commitments to reduce the use of virgin plastic, which will stimulate the recycling market. "When big companies change, they can move markets and send important signals across the economy," MacKerron says.

He sees two competing visions for the future of plastics: industry players tout chemical recycling as a fix to plastic pollution, while activists want to ban plastic. The most likely path is somewhere in between, he says.

"When big companies change, they can move markets and send important signals across the economy."

Alain Marty

» **Chief scientific officer, Carbios**

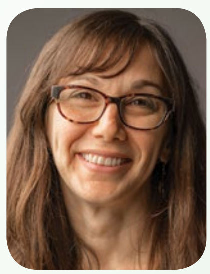
Alain Marty is proud of Carbios's biological process for recycling complex polyethylene terephthalate (PET) waste such as multilayer bottles and textile fibers. The company's enzyme, produced by a fungal strain, is a "molecular scissor" that breaks down PET into terephthalic acid and ethylene glycol by snipping the ester bond between them.

Unlike conventional mechanical recycling, the process being promoted by the France-based company can recycle PET that is colored, opaque, and mixed with components like titanium dioxide, cotton or nylon fibers, and pigments. The enzyme's activity doesn't get tripped up by postconsumer plastic.

Carbios is building a demonstration plant that will go into operation next year and process hundreds of metric tons of plastic, Marty says. An industrial plant that will process tens of thousands of metric tons of plastic is planned for 2023.

The process depolymerizes 97% of PET starting materials into monomers in 24 h. For each kilogram of PET, the process requires about 1 g of enzyme, which Marty says is a small amount. The enzyme is very thermostable, so it can be reused several times, he says. A recent agreement with leading enzyme producer Novozymes should make enzyme production more efficient, thus reducing costs. "We are able to produce around 10 g per liter of enzyme," Marty says. "Novozymes will be able to produce these enzymes more efficiently."

Chelsea Rochman



» **Assistant professor, University of Toronto**

Chelsea Rochman has been trying to understand the environmental impact of

CREDIT: ALL IMAGES COURTESY OF INSTITUTIONS plastic pollution for over 10 years, and her work has had international policy implications. She focuses on the sources, fates, and effects of microplastics, which pose a concern physically and because of the chemicals and additives they leach. "We don't know what's exactly in the leachate, but some of it can be toxic," Rochman says.

Smaller than 5 mm, microplastics are difficult to quantify and characterize, so Rochman's lab develops new collection and analysis techniques. Commercial Raman spectrometers come with spectral libraries to identify samples, but those spectral fingerprints tend to be for pure polymers rather than real-life plastic. "We've created a library that includes particles with dyes, additives, and morphologies, so we can identify the polymer type of particles we used to get unknowns for," she says.

A study in Lake Ontario revealed over 100 microfibers and particles in the gastrointestinal tract of a single fish. To test if these microfibers, shed from clothing and carpets, can be mitigated at the source, her team is installing filters in washing machines in over 100 households in Parry Sound, Ontario. The filters removed 90% of microfibers in lab tests, she says.

A deeper understanding of microplastic impact could help inform meaningful policy decisions, Rochman says. Her research was influential in the recent multicountry ban on the plastic microbeads found in beauty products. "There's no one-size-fits-all solution to microplastics," she says.

Joe Vaillancourt

» **CEO, Agilyx**

For Joe Vaillancourt, chemical recycling is necessary to increase plastic recycling rates. His Oregon-based company has, over the past 15 years, perfected a "polymer agnostic" pyrolysis technology that can convert a broad range of hard-to-recycle waste plastics into high-value synthetic crude oils, chemicals, or discrete monomers (see page 8). "We are the only company that can produce all three," he says. The products have 50–70% less carbon emissions than those made from petrochemical crude.

The company targets mixed, low-grade, and contaminated plastics that today's mechanical recycling cannot handle. Unique to Agilyx's process is the absence of catalysts, which can be poisoned in the presence of complex plastic substrates. This feature allows the firm to use a wider feedstock range.

Falling oil prices in 2014 led Agilyx to pivot its business to polystyrene, which has a 1% global recycling rate. Partnering with polystyrene refiner and producer Americas Styrenics, the company retrofitted its plastic-to-oil facility in Tigard, Oregon, to convert 10 metric tons (t) of waste polystyrene per day into food-grade styrene monomers. They are now planning to develop several polystyrene recycling facilities with Americas Styrenics and another partner, Ineos Styrolution, across the US at 5–10 times the Tigard scale.

"We can take those carpets back to food-grade bottles."

The company is now looking ahead to polyethylene terephthalate (PET). Unlike mechanical recycling, which converts PET bottles into lower-value products like carpets, "we can take those carpets back to food-grade bottles," Vaillancourt says. In a partnership announced in December, Agilyx will apply GE's artificial intelligence to its extensive database of chemical conversions and polymer recipes. The companies aim to boost all plastic recycling rates from today's approximately 10% to 95% using chemical recycling. "If we really want this to work, everybody needs to work together," Vaillancourt says.

Jeff Wooster

» **Global sustainability director, Dow Packaging and Specialty Plastics**

After spending the first half of his 30-year career developing high-performance plastics packaging systems, Jeff Wooster says he switched to sustainability "to create solutions to drive success but also make the world a better place for people."

While recycling is one solution for sustainability, getting government agencies and private companies to work together is also important. Dow helped launch the Alliance to End Plastic Waste, a nonprofit backed by 40 global businesses that has committed $1.5 billion to help eliminate plastic pollution in the environment. The alliance's goals are to work with regional agencies in Southeast Asia, a major source of marine plastic pollution, to demonstrate waste management systems and technology solutions and to create new markets for waste plastic.

"The plastic recycling market is going to grow substantially in the next 10 years."

Using chemically recycled feedstock from Fuenix Ecogy Group (see page 15) to make new plastics, Dow plans to incorporate at least 100,000 t of recycled plastics in products sold in the European Union by 2025. The company is also thinking creatively about uses for recycled plastic and is piloting programs to use polymers in bricks and asphalt.

"The plastic recycling market is going to grow substantially in the next 10 years," Wooster says. "Brands want to increase recycled content. If consumers buy more products made with recycled content, companies will work to meet that demand."

BY THE NUMBERS

Trace what happens to plastic after it goes in the recycling bin

New lease on life

Recycled plastics tend to differ in applications compared with their never-before-used counterparts.

	1 Polyethylene terephthalate	2 High-density polyethylene	3 Polyvinyl chloride	4 Low-density polyethylene	5 Polypropylene	6 Polystyrene	7 Other
Common applications of virgin plastic	Carbonated beverage bottles, water bottles, heatable food trays	Noncarbonated beverage (e.g., milk) containers, grocery bags, household chemical bottles	Pipe, windows, synthetic leather, medical tubing, automotive product bottles	Flexible films (e.g., trash bags, bread bags, dry cleaning garment bags); squeeze bottles	Straws, cups, yogurt containers, ketchup bottles, hangers, automobile battery casings	To-go containers, hot and cold cups, flatware, foam packing, trays for meat or fish	Nylon, polycarbonate, polylactic acid, multilayer packaging, safety glasses, lenses
Mass discarded in US, 2017 (billion kg)	4.54	5.58	0.87	7.33	7.26	2.13	Data not available
Percentage recycled in US, 2017	18.2%	9.4%	Negligible	4.2%	0.6%	0.4%	Data not available
Common applications of recycled plastic	Clothing, carpet, carbonated beverage and water bottles, clamshell containers	Decking, flower pots, crates, pipe, detergent bottles	Pipe, siding, carpet backing, flooring	Trash bags, decking, shipping envelopes, compost bins	Paint cans, speed bumps, plant pots, toothbrush holders, hangers	Picture frames, crown molding, tape dispensers, hangers, toys	Electronic housings, auto parts

How much does recycling plastics save annually?

» Energy

Equivalent to

983,000

households' electricity use

» Water

Enough to fill

130

Olympic swimming pools

» Solid waste

Equivalent to the weight of

186

Boeing 747 airplanes

» Greenhouse gas emissions

Equivalent to taking

254,000

passenger vehicles off the road for a year

Sources: American Chemistry Council, Association of Plastic Recyclers, Environmental Protection Agency, More Recycling.

Notes: Applications of recycled plastic may vary in the amounts of recycled content. Markets for recycled plastic vary depending on supply and demand. Data on savings from plastic recycling are from 2015. To arrive at these estimates, environmental costs of producing virgin material, recycling that material, and ultimately disposing of recycled products were shared among all of a material's useful lives.

ANALYSIS

Agilyx takes all sorts of polystyrene waste at its Tigard, Oregon, plant.

Plastic has a problem; is chemistry the solution?

ALEX TULLO, C&EN NEW YORK CITY

Business is taking off for Agilyx. In 2018, the small company opened a plant in Tigard, Oregon, that uses pyrolysis to break down about 10 metric tons (t) per day of polystyrene waste into its starting material, styrene.

Big chemical companies have since been beating a path to Agilyx's door. Ineos Styrolution plans to use Agilyx's technology to build a plant in Channahon, Illinois, that will process 100 t of polystyrene waste per day.

And the Tigard plant itself is now part of a joint venture with the polystyrene maker Americas Styrenics. The two firms are close to announcing a new plant, with 50 t per day of capacity, in the western US. Trinseo and Ineos Styrolution are planning yet another Agilyx depolymerization plant in Europe.

"This last year and a half has been very frenetic," says Joseph Vaillancourt, Agilyx's CEO. "Lots of opportunities; very exciting. There is still a lot coming that we haven't disclosed yet."

Agilyx, Vaillancourt says, is working with 30 companies in total on projects at various stages of development, including efforts in polyethylene terephthalate (PET) and acrylic depolymerization.

Agilyx isn't the only chemical recycling company on a steep growth trajectory. Plastic Energy, which uses pyrolysis to transform mixed plastics into diesel and naphtha, plans to build 10 plants in both Asia and Europe by 2023, including 1 at Sabic's chemical complex in the Netherlands. Loop Industries is building a commercial plant to break down PET into its raw materials in Spartanburg, South Carolina, as part of a joint venture with the big polyester maker Indorama. And Loop aims to build three more plants by 2023.

The projects are signs that the plastics industry is placing a big bet on chemical recycling as it comes under intense pressure to do something about plastic waste.

Plastics are under assault as they haven't been in a generation. Documentaries showing beaches cov-

CREDIT: AGILYX

ered in debris and sea turtles tangled in plastics have turned the public against the material.

Consumer product companies such as Coca-Cola, PepsiCo, and Unilever have made ambitious commitments to incorporate recycled material in their packaging, up to 50% in some cases. Governments are seeking bans on single-use plastics like straws and are mandating greater use of recycled content.

But brand owners don't want to compromise on performance. And they would if they depended on traditional mechanical recycling processes, which merely wash the plastics and melt them down again. Chemical recycling methods that recover their original raw materials to be remade into high-quality resins offer a way out.

Plastics producers are eager to give chemical recycling a try, and dozens of start-ups are ready to help them. But they face challenges. To have a chance at making the technique profitable, they need to build big, expensive plants and aggregate a lot of plastic waste.

Critics say they will never be able to ramp up the technology fast enough to make a dent in the problem. Chemical makers say they can—and in the process establish a circular economy for plastics.

The dysfunction of plastics recycling

Plastics recycling, as it exists today, is a mess. In 2015, the US recycled only 9.1% of the 31 million t of plastics that consumers threw out, according to the Environmental Protection Agency. The vast majority ended up in either landfills or incinerators. In contrast, two-thirds of paper, a third of metals, and a quarter of glass were recycled that year. In the European Union, about 14.8% of the roughly 27 million t of plastic waste was recycled in 2016, according to the European Commission.

Plastics recycling is a battle against entropy. Consumers throw plastics of all sorts into curbside bins, where they get mixed with metal and glass. From this assorted waste, recycling facilities use optical sorters to pluck out only the most valuable plastics for reuse.

Recycling facilities are most interested in PET beverage bottles and high-density polyethylene containers like milk jugs—plastics numbers 1 and 2, respectively. They are relatively clean and homogeneous materials, and recyclers handle enough of them to make extraction worthwhile. Secondary processors wash, melt,and repelletize them for reuse.

Some of the other residual plastics— polypropylene yogurt cups and multilayer plastic pouches, for example—are baled and carted off to processors that attempt to extract additional plastics of some value. But most go to landfills.

Even desirable number 1s and 2s that are sorted out of curbside streams are difficult to recycle. They are contaminated with food and grime. Not all plastics with the same name and number are actually the same: the PET used in a takeout container is different from that used in a water bottle.

“If you look at the amount of recycled content in the plastic industry that companies are committing to, they are not going to be able to reach that with the mechanical technologies that exist today.”

For all these reasons, plastics are usually downcycled into applications with less-exacting specifications than what the virgin materials were designed for. A soda bottle doesn't become a soda bottle again; it is made into a carpet or a fleece vest. In its next incarnation, the milk jug becomes the inner layer of a detergent bottle.

To Nina Bellucci Butler, CEO of the consulting firm More Recycling, the economics are stacked against building an adequate recycling infrastructure. “There are a lot of inefficiencies in the marketplace,” she says. “Even those companies that make major strides to reduce environmental impact don't realize the reward or competitive advantage because not all claims of recycled content or recyclability have adequate oversight or transparency. Also there is a failure to incorporate the environmental cost and benefit in using virgin materials versus recycled or the full environmental impact of land filling our resources.”

For instance, Butler says, tipping fees—the cost municipalities pay to landfill plastics and other trash—are too low, reducing the incentive to try to recover value from waste plastics.

So are the prices of virgin plastics that recycled materials are supposed to compete with. In the early 2010s, Butler says, companies were investing in, and plastic goods makers were increasingly using, recycled material. That faded when oil prices tumbled. Recycling isn't attractive when oil is below $100 per barrel, she says. “Companies aren't ready to pay 20% premiums for a product that is not at the same level of quality as virgin unless there is a marketplace incentive to producing a product with a lower carbon footprint.”

Chemical recycling could be a way around some of mechanical recycling's shortcomings. Chemical processes are more tolerant of contamination, and they yield polymers that are identical to the originals, eliminating downcycling. Extracting more value from waste plastics this way, proponents say, could provide industry with the incentives and money it needs, perhaps creating a virtuous cycle.

“If Agilyx can source and treat the material so that it enables them to produce at low cost so it can actually compete one for one with virgin, that would be such a beautiful game changer,” Butler says.

The chemical option

Executives at companies developing depolymerization processes to break PET into raw materials are keen to talk up their advantages, such as being able to handle every bale of PET that lands on their loading docks.

One such executive is Martin Stephan, deputy CEO of the French start-up Carbios. The company is developing a process to break down PET into purified terephthalic acid (PTA) and ethylene glycol with an engineered enzyme. It is building a demonstration plant, which will cost around $10 million, near Lyon, France.

Mechanically recycling waste PET into new bottles requires pristine, transparent raw mate-

Pyrowave is testing a process that uses microwaves to break down polystyrene into styrene.

rials, Stephan explains. Moreover, PET degrades every time it is reprocessed; after about six cycles it's no good.

Carbios's approach has no such limitations, Stephan says. "Conceptually, it is an infinite recycling process," he says. "You can depolymerize any kind of PET waste and make any kind of PET product. You can make a black transparent bottle using a black T-shirt as a feedstock, or you can make a black T-shirt using a transparent bottle."

Stephan says Carbios's process can tolerate high levels of impurity. The enzyme just ignores the impurities as it finds the PET polymer in the reactor and breaks it down.

Loop Industries' process is explicitly designed for flexibility. The firm was founded in 2014 to use hydrolysis to break down PET into PTA and ethylene glycol. It shifted to using methanolysis to make dimethyl terephthalate, an alternative PET raw material, because the purification is much easier, CEO Daniel Solomita says. "The drawback of PTA is that it is difficult to purify," he says.

The change made it easier for the company to remove the dyes, pigments, foreign polymers, and even ketchup and mayonnaise that can end up in bales of waste PET. The material Loop will process will contain on average 15% contamination, Solomita says.

Loop's Spartanburg joint venture with Indorama was initially proposed to process about 20,000 t of plastic per year. It will handle mostly materials that mechanical recyclers rarely touch, such as PET clamshells, microwave trays, and carpeting. "There is an abundance of material on the market that there is no solution except for Loop's," Solomita says.

Pyrolysis plants are even more omnivorous than depolymerization facilities. Pyrolysis cracks long polymer chains into short-chain hydrocarbons like diesel and naphtha under low-oxygen conditions and temperatures of more than 400 °C.

One polymer that pyrolysis plants don't like is PET because it contains oxygen. Thus they have a symbiotic relationship with mechanical recyclers, which have a preference for PET soda and water bottles anyway.

Pyrolysis is best suited to handle a mixture of polyethylene and polypropylene. While pyrolysis today is focused mostly on fuels, chemical companies hope that more firms will use the process to make naphtha, which can be fed into petrochemical plants and become polyethylene and polypropylene again.

"I would like to have the plant tomorrow, to be honest with you."

Brightmark Energy has one of the largest such projects. It has started construction on a $260 million plant in Ashley, Indiana, that will transform 100,000 t per year of plastic waste into 68 million L of diesel and naphtha, which it will sell to BP, and 22 million L of industrial wax.

The feedstock will be mixed plastic leftovers from recycling operations in Northeast Indiana, says Brightmark CEO Bob Powell. Brightmark will open the bales, remove contaminants such as aluminum cans, and then shred, dry, and pelletize the plastic before it is sent to the reactor.

Powell wants the company to evolve away from producing fuels for combustion and focus on naphtha for making plastics again. "Ultimately, the output of this process will be used to create a high proportion of plastic feedstock," he says. "It is achievable; it can be done with this facility. It will really help with the circular economy."

This is precisely the idea Dow has in mind for its partnership with the Dutch start-up Fuenix Ecogy. Dow plans to feed a naphtha-like oil from Fuenix's pyrolysis process into Dow's petrochemical plant in Terneuzen, the Netherlands.

"The beautiful thing about feedstock recycling is that you take waste plastic, you make a pyrolysis oil, and at the end of the day you make a virgin plastic," says Carsten Larsen, who directs recycling in Europe and Asia for Dow's plastics business. "You have a 100% normal grade of food-approved plastic, except instead of coming from fossil fuels, itcomes from waste plastic."

It is not clear yet how much naphtha Dow will be able to procure, but the company took its first delivery of raw material in August 2019. The company's goal for Europe is to incorporate 100,000 t of recycled plastic in its polymers by 2025, both through mechanical recycling and the partnership with Fuenix. "The challenge for us as a company is now going to be to scale this solution in quantities that are relevant for the industry," Larsen says.

While chemical recycling appeals to manufacturers, it would ideally offer environmental bene-

Brightmark Energy is spending $260 million to build this plastic pyrolysis plant in Ashley, Indiana.

fits beyond waste reduction. Marco J. Castaldi, director of the Earth Engineering Center at the City College of New York, puts chemical recycling a rung below mechanical recycling in terms of greenhouse gas emissions efficiency because of the extra steps and heat involved in the process. On the other hand, "When you have recycling where you are decomposing, bringing it back to its monomers, and reconstructing it, that's still good," he says. "That's obviously better than disposing of it."

A 2017 study from Argonne National Laboratory found that producing low-sulfur diesel fuel via pyrolysis of waste plastics is up to 14% less greenhouse gas intensive than making the same fuel from crude oil.

Similarly, a study published last year by the Dutch think tank CE Delft estimated that widespread adoption of chemical recycling in the Netherlands would reduce greenhouse gas emissions by about 300,000 t per year. The researchers found that by avoiding production of virgin materials, depolymerization saves 1.5 t of CO_2 per metric ton of plastic recycled. Mechanical recycling saves 2.3 t.

Although chemical recycling offers some environmental benefits, Neil Tangri, science and policy director for the environmental group Global Alliance for Incinerator Alternatives, is skeptical it will be a significant solution.

With global plastics production growing 3–4% per year, he thinks a cap on output is a better approach. "There is no way any downstream solution, no matter how good the technology is, is going to scale up and keep pace with that level of production," he says.

Chemical recycling proponents would love to prove Tangri wrong. They want nothing more than to be able to scale up their processes, consume more waste, and survive economically.

"I have looked at the economics under a number of different conditions, and it is pretty scale dependent," says Mark Morgan, vice president of chemical consulting at IHS Markit. For example, a pyrolysis plant with 15,000 t of annual capacity, processing polyolefins, could produce hydrocarbon oil at a cost of about $800 per metric ton in North America and $1,000 per metric ton in Europe. If the plant has a capacity of 55,000 t, costs drop to $500 and $600, respectively.

CREDIT: PYROWAVE (MICROWAVES); BRIGHTMARK ENERGY (PLANT)

"Plastic is still fantastic. But the end of life of plastic has not been thought through enough."

These larger plants should be close to large sources of feedstock, Morgan says. "I do not see a business case for very long-distance movement of plastic waste to do chemical recycling with," he says.

Morgan has firsthand knowledge. In the early 1990s, he was with BP when the company was developing a pyrolysis-like process that would have supplied feedstock to its ethylene plant in Grangemouth, Scotland. Part of the problem was that the waste plastics had to be trucked in from a long distance.

The economics of procuring feedstocks depend on the product a company wants to make, Morgan says. A company depolymerizing PET will likely be able to pay more for its raw material and ship it longer distances than a company trying to break down mixed plastics into lower-value naphtha or synthetic fuel.

Cloé Ragot, head of policy and sustainability at Plastic Energy, says her firm has the fortune of being close to both raw materials and customers with its project in the Netherlands. It is building a waste plastic pyrolysis facility on Sabic's site in Geleen and will supply the petrochemical giant the plant's naphtha-like output as a raw material.

The plant will have about 20,000 t of annual capacity and run on waste acquired locally by the waste management firm Renewi. "Basically, it is the leftover from mechanical recyclers," Ragot says. Most of the material, she says, will be low-density polyethylene, polypropylene, and some polystyrene that otherwise would have been incinerated.

The company has operated two plants in Spain for 4 years that supply diesel and naphtha to the Spanish oil company Repsol.

On its way to establishing 10 plants in Asia, Plastic Energy is planning a plant in Malaysia and five in Indonesia. Feedstock sourcing will be a challenge in a region where plastic is not yet separated from the rest of the trash, Ragot acknowledges. "There is very little sorting infrastructure, which means that the plastic is really contaminated, mainly by food waste," she says.

The value in plastic waste

Economics has driven Agilyx to completely change its business model over the years. The company started by making fuels in its pyrolysis process in 2004. Agilyx transitioned in 2018 to making styrene from polystyrene by modifying its pyrolysis process somewhat and also using polystyrene as a raw material. It made the change largely because styrene sells for more.

"In the commodity market, you have a lower return on fuels; you will have a little bit better return on naphtha and some pretty interesting returns on discrete polymers," Vaillancourt says.

Making a higher-value product allowed Agilyx to cast a wider geographical net for polystyrene waste. "It is much more financially attractive to build larger regional facilities" that are near contract customers, Vaillancourt says. This is as opposed to smaller, local facilities. “We found ways to be economical around aggregation of feedstock.”

Agilyx has built a network of 500 qualified feedstock suppliers. For the Tigard plant, the company accepts feedstock from as far away as a school lunch program in Florida. The company pays for the plastic, gets it for free, or in some cases, gets paid to take it. On balance, Vaillancourt says, Agilyx pays nothing.

Vaillancourt’s advice to other chemical recyclers is to align with a partner that will buy predictable volumes of a single product. “We won’t develop any project without a committed partner,” he says.

Agilyx has an enthusiastic partner in Ineos Styrolution, which hopes to open the Illinois plant in 2022. “I would like to have the plant tomorrow, to be honest with you,” says Ricardo Cuetos, the firm’s vice president of standard products.

In October 2019, at the K plastics show in Düsseldorf, Germany, Ineos Styrolution announced a new product line incorporating the recycled polystyrene resins. It will be geared toward food-contact use, an application that is not appropriate for polystyrene that is mechanically recycled.

Actually, very little polystyrene is recycled at all, Cuetos says, but he thinks chemical recycling will change that. “There was no end market for polystyrene. It was just benches and picture frames or things like that,” he says. “Now we are closing the loop in a true circular economy. We will be taking the styrene and producing virgin material that will go into any application: food, industrial, everything.”

At every stage of the process, Cuetos predicts, companies will profit and preserve the original value of the polymer. “I think it is really going to help boost the collection of polystyrene,” he says.

Single-use polystyrene foam products are a favorite target of politicians. New York City, for instance, banned polystyrene food-service clamshells this year. Cuetos wonders what will happen if polystyrene becomes 100% recyclable. “I hope that will change the public perception and mind-set,” he says.

Carbios is developing a process to break down polyethylene terephthalate into purified terephthalic acid and ethylene glycol using enzymes.

In the hopes of reversing polystyrene’s fortunes, Ineos Styrolution is betting on a few approaches to polystyrene recycling. It is working with GreenMantra Technologies, which makes synthetic waxes and polymer additives from waste plastics. And it is in a partnership with Pyrowave, which uses microwave radiation to break down the polymers.

Consumer product companies, many of which have big commitments to use recycled plastic, are lining up to buy chemically recycled material. Coca-Cola aims for 50% recycled content by 2030. Pepsi wants to average 33%, Nestlé Waters is shooting for 50%, and Unilever aims to achieve 25%, all by 2025.

Governments are also pushing companies to use more recycled plastic. California wants beverage containers to hit 50% recycled content by 2030. The European Union is pushing for 30% by the same date.

“If you look at the amount of recycled content in the plastic industry that companies are committing to, they are not going to be able to reach that with the mechanical technologies that exist today,” says Bridget Croke, vice president of external affairs at Closed Loop Partners, which studies and invests in recycling technologies. “They’re going to need new ways to be able to get that plastic back so that the quality of material is high enough to get into packaging again.”

Many of the companies in chemical recycling expect that consumer goods giants will be willing to pay a premium for their products so they can meet their recycling targets. Indeed, big customers are placing orders.

Loop Industries has supply agreements in place with Coca-Cola, Danone, and Pepsi. The material from the upcoming Spartanburg plant is spoken for, and the partnership is already considering doubling capacity to 40,000 t. “We are looking at potentially going bigger because demand is so overwhelming,” Solomita says. The company is also considering plants on the West Coast, in Canada, and in Europe.

Similarly, Tupperware and Unilever are beginning to use polymers resulting from Plastic Energy’s partnership with Sabic. For example, in August, Unilever launched ice cream tubs under its Magnum brand incorporating the material.

The commitments to use recycled material are a sign that consumer product makers realize they need real change to mitigate the backlash against plastic. Chemical recycling hasn’t proved it will be the means by which they will keep those promises, but companies of all types are betting that the technology will be a part of the solution.

“Plastic is still fantastic,” Carbios’s Stephan says. “But the end of life of plastic has not been thought through enough. We need to find solutions to continue to use plastic.”

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CREDIT: CARBIOS

COMPANIES TO WATCH

Our primer on 32 firms using depolymerization, pyrolysis, or other methods to chemically recycle plastics

apc
Agile Process Chemicals LLP

» **www.pyrolysisplant.com**
» **Based:** Mumbai, India
» **Founded:** 2007
» **Money raised to date:** Not available
» **Key partnerships:** Not disclosed
» **Strategy:** The pyrolysis technology offered by Agile Process Chemicals converts plastic and tire waste into pyrolysis oil, which can be used as a fuel in electricity generators; carbon black, a replacement for coal; and hydrocarbon gas.
» **Why watch:** Though it has not disclosed funding or partnerships, Agile Process has set up more than 35 pyrolysis plants in far-flung locations, including Kenya, the United Arab Emirates, and the UK. The company says that each day its plants prevent over 75,000 kg of plastic waste from entering landfills.

agilyx

» **www.agilyx.com**
» **Based:** Tigard, Oregon
» **Founded:** 2004
» **Money raised to date:** $61.3 million
» **Key partnerships:** Delta Air Lines, Americas Styrenics, Ineos Styrolution
» **Strategy:** The mixed-plastics-to-crude platform from Agilyx converts difficult-to-recycle waste plastic into a synthetic crude oil that is sold to refineries to make gasoline, lubricants, and even new plastics. And its technology breaks down polystyrene—a notoriously intractable plastic—to a styrene monomer oil that is ready to refine into new products.
» **Why watch:** The growing firm announced in December a partnership that will leverage GE's artificial intelligence technology for chemical recycling, and in January it secured a round of financing from European investors, with plans for an office in Oslo, Norway.

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

奥生 OURSUN

» **www.oursunchina.com**
» **Based:** Hefei, China
» **Founded:** 2004
» **Money raised to date:** Not available
» **Key partnerships:** Anhui Oursun Resource Technology was established as a joint venture between partners in China, Taiwan, and the US.
» **Strategy:** With help from a patented plastic-cracking catalyst formulation, Oursun Resource's facilities transform polyethylene, polypropylene, and polystyrene waste plastics to diesel oil, gasoline oil, gas, and slag.
» **Why watch:** An analysis from Transparency Market Research suggests that the Asia-Pacific region accounts for about 44% of the global market for plastic waste to oil in terms of revenue, with China dominating that space.

Axens
Powering integrated solutions
An IFP Group company

» **www.axens.net**
» **Based:** Rueil-Malmaison, France
» **Founded:** 2001
» **Money raised to date:** Not available
» **Key partnerships:** Not disclosed
» **Strategy:** Axens is a worldwide group that provides furnaces, catalysts, adsorbents, and other services for the refining and petrochemicals industries. It has developed a process that depolymerizes polyethylene terephthalate into the monomer bis(2-hydroxyethyl) terephthalate.
» **Why watch:** The process has so far been validated on lab scale only, but the firm is hunting for partners to build a pilot plant.

BioCellection

» **www.biocellection.com**
» **Based:** Menlo Park, California
» **Founded:** 2015
» **Money raised to date:** $5 million
» **Key partnerships:** City of San Jose, California; GreenWaste Recovery
» **Strategy:** BioCellection focuses on the flexible polyethylene plastics in grocery bags and bubble wrap. The firm's selective oxidation chemistry, accelerated thermal oxidative depolymerization, transforms the plastic to lower-molecular-weight organic acids such as succinic acid and adipic acid, which are precursors for polyesters and nylon, respectively.
» **Why watch:** The women-led firm announced in October that it had received an investment from Japanese start-up hub Mistletoe, which has supported 190 start-ups and venture funds in 15 countries.

Blest
Protect earth from contamination

» **www.blest.co.jp/eng**
» **Based:** Kanagawa, Japan
» **Founded:** 2001
» **Money raised to date:** Not available
» **Key partnerships:** Not disclosed
» **Strategy:** Blest manufactures and distributes both batch and continuous pyrolysis technology that targets polyethylene, polypropylene, and polystyrene feedstock. Its process produces a mix of diesel, gasoline, kerosene, and heavy oils.
» **Why watch:** Blest machines have been deployed in 41 countries, including Palau and Canada. The company also sells a $10,000 household appliance that converts plastic bags to fuel.

BME Brightmark Energy

» **www.brightmarkenergy.com**
» **Based:** San Francisco
» **Founded:** 2016
» **Money raised to date:** $260 million
» **Key partnerships:** BP, RecycleForce, AM Wax
» **Strategy:** Brightmark's forthcoming plastics-to-fuel plant in Indiana will use pyrolysis to convert mixed single-use plastics sourced from Indiana and Chicago-area waste and recycling companies into a hydrocarbon liquid that can be processed into commercial-grade ultra-low-sulfur diesel, naphtha, and wax.
» **Why watch:** Partner RecycleForce will provide Brightmark with e-waste plastics—a recycling challenge—for processing.

CARBIOS
Reinvent Polymers Lifecycle

» **www.carbios.fr**
» **Based:** Saint-Beauzire, France
» **Founded:** 2011
» **Money raised to date:** $19.9 million
» **Key partnerships:** CNRS, L'Oréal, Novozymes
» **Strategy:** Carbios has optimized an enzyme that in just 24 h depolymerizes polyethylene terephthalate into terephthalic acid and ethylene glycol in 97% yield.
» **Why watch:** In 2019, Nestlé Waters, PepsiCo, and Suntory Beverage & Food Europe signed on to a Carbios-and-L'Oréal-founded consortium to use Carbios's enzymatic technology (see page 6).

eft
ecofuel technologies

» **www.ecofueltechnology.com**
» **Based:** Livonia, Michigan
» **Founded:** 2012
» **Money raised to date:** Not available
» **Key partnerships:** SAIC, Save Our Oceans Foundation
» **Strategy:** The company's proprietary nanoengineered catalysts depolymerize polyethylene, polypropylene, and polystyrene to diesel or gasoline that can be used in engines with no further refining.
» **Why watch:** The firm's team in India is building reactors that can process 227 or 907 kg of plastic per day.

enval

» **www.enval.com**
» **Based:** London
» **Founded:** 2005
» **Money raised to date:** $2.8 million
» **Key partnerships:** Kraft Foods, Nestlé
» **Strategy:** With microwave-induced pyrolysis, Enval processes multilayer packaging in which aluminum foil is sandwiched between plastic layers—the kind used for pet food, juices, and cosmetics. The result is recovered aluminum foil; hydrocarbon gas, which can be harvested to power additional pyrolysis; and hydrocarbon oils, which can be sold to make fuel or specialty chemicals.
» **Why watch:** Enval and partner Little Freddie, an organic baby food company, launched a mail-in pouch recycling program that will soon surpass half a million items collected.

Sources: Crunchbase (accessed January 2020), Closed Loop Partners, company websites, news reports.

fuenix

Let no plastic go to waste

» **www.fuenix.com**
» **Based:** Weert, Netherlands
» **Founded:** 2013
» **Money raised to date:** Not available
» **Key partnerships:** Dow
» **Strategy:** Fuenix Ecogy's process converts postconsumer mixed-waste plastics into naphtha, paraffin, and liquefied petroleum gas.
» **Why watch:** The company says the polymers resulting from its Dow pyrolysis partnership will be indistinguishable from those made with traditional feedstocks, so they can be used in exacting applications such as food packaging (see page 10).

GARBO

your innovative partner

» **www.garbosrl.net/?lang=en**
» **Based:** Cerano, Italy
» **Founded:** 1997
» **Money raised to date:** Not available
» **Key partnerships:** Indorama, Plastipak, Ikea
» **Strategy:** The company's ChemPET project uses glycolysis to depolymerize polyethylene terephthalate to the monomer bis(2-hydroxyethyl) terephthalate. The breakdown and a subsequent purification take less than 6 h combined.
» **Why watch: I**n the long term, Garbo plans to polymerize the monomer and sell the resulting polymer.

Golden Renewable Energy

» **www.goldenrenewable.com**
» **Based:** Yonkers, New York
» **Founded: 2010**
» **Money raised to date:** Not available
» **Key partnerships:** Not disclosed
» **Strategy:** Golden Renewable Energy's pyrolysis technology turns mixes of plastics from residential, commercial, and industrial wastes into a diesel fuel that is comparable to a common home-heating fuel.
» **Why watch:** The company has raised funds from Fortistar, a private investment and energy management firm.

gr3n

REDUCE REUSE RECYCLE

» **www.gr3n-recycling.com**
» **Based:** Castagnola, Switzerland
» **Founded:** 2013
» **Money raised to date:** $13.4 million
» **Key partnerships:** H&M, Adidas, Coca-Cola
» **Strategy:** By applying microwave technology to hydrolysis, Gr3n depolymerizes polyethylene terephthalate into terephthalic acid and ethylene glycol.
» **Why watch:** Gr3n's network spans the entire value chain; in addition to brands, the company counts PET producers, municipalities, and equipment makers as partners.

GREENMANTRA TECHNOLOGIES

» **www.greenmantra.com**
» **Based:** Brantford, Ontario
» **Founded:** 2010
» **Money raised to date:** $24.3 million
» **Key partnerships:** Sun Chemical, Bioindustrial Innovation Canada
» **Strategy:** GreenMantra's thermocatalytic process transforms postconsumer and postindustrial polyethylene and polypropylene into waxes and additives that can be used in asphalt roofing, asphalt roads, polymer-processing applications, or plastic composites.
» **Why watch:** The company plans to begin operating a demonstration facility for processing polystyrene and has inked an agreement with plastics maker Ineos Styrolution to have its product evaluated as a raw material for polystyrene production.

ioniqa

» **www.ioniqa.com**
» **Based:** Eindhoven, Netherlands
» **Founded:** 2009
» **Money raised to date:** $16.2 million
» **Key partnerships:** Unilever, Indorama Ventures
» **Strategy:** Ioniqa breaks down polyethylene terephthalate with a glycolysis reaction catalyzed by magnetic metal particles. The chemistry produces the monomer bis(2-hydroxyethyl) terephthalate.
» **Why watch:** In October 2019, Ioniqa announced that Coca-Cola used its technology to create proof-of-concept soft-drink bottles from plastic recovered from the Mediterranean Sea and beaches.

JEPLAN

Japan Environment PLANning

» **www.jeplan.co.jp/en**
» **Based:** Tokyo
» **Founded: 2007**
» **Money raised to date:** Not available
» **Key partnerships:** Nippon Steel Sumitomo Metals, Starbucks Japan
» **Strategy:** The company touts its two-pronged approach. The first strategy is a glycolysis-Based chemical depolymerization for polyethylene terephthalate from bottles or polyester textiles. The process yields the monomer bis(2-hydroxyethyl) terephthalate, which can be used to make new textiles. The second strategy harnesses pyrolysis to recover oil and metals from e-waste.
» **Why watch:** Uniforms for the 2020 Olympics in Tokyo will contain recycled textiles from Jeplan.

KleanIndustries

Renewable energy, resource recovery & recycling

» **www.kleanindustries.com**
» **Based:** Vancouver, British Columbia
» **Founded:** 2005
» **Money raised to date:** Not available
» **Key partnerships:** Dow, Bayer, BASF, Toshiba
» **Strategy:** Klean's pyrolysis, liquefaction, and gasification systems can handle even difficult-to-recycle plastics such as polyvinyl chloride. The firm's facilities accept agricultural plastics, tires, and e-waste alongside postconsumer plastics. The technology produces refined fuels and recovered carbon black, which can be used in new tires.
» **Why watch:** The firm has developed a blockchain-based platform that will enable recycling companies to more reliably share information about waste and recyclables with partners.

» **www.loopindustries.com/en**
» **Based:** Terrebonne, Quebec
» **Founded:** 2015
» **Money raised to date:** $35 million in IPO
» **Key partnerships:** L'Occitane, Evian, Danone, Coca-Cola
» **Strategy:** Loop depolymerizes polyethylene terephthalate (PET) from applications including plastic bottles, packaging, polyester textiles, and carpet. The platform can accept PET plastic of any color and transparency, and can even handle ocean plastic degraded by salt and the sun. After filtration and purification, the resulting monomers are repolymerized to form a virgin-quality PET resin that's suitable for use in food-grade packaging.
» **Why watch:** Loop currently operates a pilot plant in Canada but is developing a commercial facility in the southeastern US with Indorama Ventures.

» **newhopeenergy.com**
» **Based:** Tyler, Texas
» **Founded:** 2008
» **Money raised to date:** Not available
» **Key partnerships:** American Chemistry Council, Trinity Oaks
» **Strategy:** New Hope accepts postconsumer and postindustrial waste plastic of mixed colors, in particular high- and low-density polyethylene, polypropylene, and polystyrene. The company's pyrolysis process yields a variety of petroleum products, including home heating oil and asphalt.
» **Why watch:** In 2020, New Hope's Trinity Oaks plastic chemical recycling plant is expected to reach its full capacity of processing 960 t of plastic per day.

» **www.nexusfuels.com**
» **Based:** Atlanta
» **Founded:** 2008
» **Money raised to date:** Not available
» **Key partnerships:** Shell
» **Strategy:** Nexus's pyrolysis system is optimized to accept high- and low-density polyethylene, polypropylene, and polystyrene, and processes these plastics to high-grade fuels and waxes.
» **Why watch:** In November 2019, Shell announced that it had made high-end chemicals from a liquid feedstock supplied by Nexus.

» **www.perpetual-global.com**
» **Based:** Nashik, India
» **Founded:** 2008
» **Money raised to date:** Not available
» **Key partnerships:** H&M, Zara, Puma
» **Strategy:** The firm's proprietary low-temperature glycolysis platform reverse engineers postconsumer polyethylene terephthalate from bottles, polyester textiles, packaging, and film. The result is an ester compound that can be used to create polyester yarns for textiles.
» **Why watch:** The company is on track to recycle 50 million plastic bottles each day by the end of 2021.

» **www.plasticenergy.com**
» **Based:** London
» **Founded:** 2011
» **Money raised to date:** Not available
» **Key partnerships:** Sabic, Petronas Chemicals Group
» **Strategy:** Plastic Energy converts mixed plastics, multilayer plastics, contaminated plastics, and plastics that can no longer be mechanically recycled into a mixture of diesel and naphtha that can be used to create new plastics or used as alternative fuels.
» **Why watch:** The company operates two facilities in Spain but in 2019 reached an agreement to build five recycling plants in Indonesia.

» **www.polycycl.com/home.html**
» **Based:** Kalka, India
» **Founded:** 2016
» **Money raised to date:** Not available
» **Key partnerships:** Ramky Environment
» **Strategy:** PolyCycl, previously Ventana Cleantech, has patented a continuous process to transform waste plastic into fuels that can be used to substitute for diesel in industrial boilers and furnaces.
» **Why watch:** The firm's optimized platform currently yields 5.8 to 6.4 bbl of liquid fuels per metric ton of waste plastic.

» **www.pyrowave.com**
» **Based: Oakville, Ontario**
» **Founded:** 2013
» **Money raised to date:** $5.3 million
» **Key partnerships:** ReVital Polymers, Ineos Styrolution
» **Strategy:** The company's catalytic microwave depolymerization breaks down polystyrene, yielding up to 95% styrene monomer concentrate, along with waxes and oil. After purification the monomers can be used to create new, virgin-like plastics.
» **Why watch:** In January 2020, Pyrowave was awarded a grant from Sustainable Development Technology Canada to extend its platform to mixed plastics.

» **www.recyclingtechnologies.co.uk**
» **Based:** Swindon, England
» **Founded:** 2011
» **Money raised to date:** $11.9 million
» **Key partnerships:** InterChem, Kerax
» **Strategy:** Recycling Technologies

uses pyrolysis to crack waste-plastic films, bags, and laminated plastics to an oil it calls Plaxx, which can be used to produce new plastic or wax. Plaxx can also be used in burners, engines, and the shipping industry.

» **Why watch:** In December 2019, the company joined a consortium with Mars, Nestlé, and the international energy company Total that will examine the technical and economic feasibility of recycling complex plastic waste in France.

ReNew ELP

» **www.renewelp.co.uk**
» **Based:** Redcar, England
» **Founded:** 2016
» **Money raised to date:** Not available
» **Key partnerships:** Licella, Armstrong Chemicals, Neste
» **Strategy:** ReNew's Catalytic Hydrothermal Reactor uses supercritical water to convert end-of-life plastic that can't currently be recycled, such as multilayer film and containers contaminated with paper or organic matter, into hydrocarbon feedstocks such as naphtha and diesel.
» **Why watch:** ReNew is building its first commercial-scale processing facility in Teesside, England, which will process 20,000 t of plastic per year.

RENEWLOGY

» **www.renewlogy.com**
» **Based:** Salt Lake City
» **Founded:** 2011
» **Money raised to date:** Not available
» **Key partnerships:** Dow, Sustane Technologies, Western Recycling, Firstar Fiber
» **Strategy:** Renewlogy's continuous system takes in shredded plastics and uses a catalyst to degrade the polymers' long carbon chains. Approximately 75% of the chains become fuels such as naphtha, diesel, and kerosene. The rest turns into hydrocarbon gas which Renewlogy recycles to heat its system, and inert char. For every 10 t of plastic it processes, the system produces 60 bbl of fuel.

» **Why watch:** The firm is working with the city of Phoenix to open a second large-scale facility dedicated to plastics that are less easily recycled.

Resinate® Materials Group

» **www.resinateinc.com**
» **Based:** Plymouth, Michigan
» **Founded:** 2007
» **Money raised to date:** Not available
» **Key partnerships:** Ford Motor
» **Strategy:** The glycolysis process at Resinate converts postconsumer and postindustrial polyethylene terephthalate plastics to polyester polyols. These compounds are useful as components of coatings and adhesives, as well as foams for flooring, furniture, and building insulation, among other applications.
» **Why watch:** Resinate has teamed up with Ford to test its polyols' performance in automotive foam applications.

Resynergi — evolutionary energy recovery systems

» **www.resynergi.com**
» **Based:** Rohnert Park, California
» **Founded:** 2015
» **Money raised to date:** Not available
» **Key partnerships:** University of Minnesota
» **Strategy:** The firm's microwave-Based pyrolysis technology transforms high- and low-density polyethylene, polypropylene, and polystyrene to sulfur-free diesel and petrochemicals.
» **Why watch:** In September 2019, Resynergi announced a partnership with cannabis manufacturer CannaCraft to turn cannabis packaging to fuel.

TYTON BioSciences

» **www.tytonbio.com**
» **Based:** Danville, Virginia
» **Founded:** 2011
» **Money raised to date:** $8 million
» **Key partnerships:** Tin Shed Ventures (the investment arm of outdoor apparel brand Patagonia)
» **Strategy:** The company recycles discarded clothing as well as polyethylene terephthalate plastics using subcritical water technology. Its platform's output includes the monomers terephthalic acid and ethylene glycol.
» **Why watch:** Tyton brought aboard Julie Willoughby as chief scientific officer in November 2019. Willoughby, a chemical engineer, has worked for Nike and Dow Corning.

VADXX — Plastic To EcoFuel

» **www.vadxx.com**
» **Based:** Cleveland
» **Founded: 2009**
» **Money raised to date:** Not available
» **Key partnerships:** Not disclosed
» **Strategy:** Vadxx's proprietary process converts waste plastic into the company's EcoFuel, a mix of diesel fuel, naphtha, waxes, syngas, and solid-carbon products.
» **Why watch:** The company's current commercial facility in Ohio processes 25,000 t per year of plastic waste. But Vadxx has plans for plants on multiple continents.

MOVERS AND SHAKERS

Polystyvert: Recycling polystyrene with the help of a natural solvent

ALEX TULLO, C&EN NEW YORK CITY

Confronted by a public increasingly outraged about plastic waste, industry is clamoring for solutions. Dozens of start-ups have sprouted with recycling technologies that claim to yield high-quality materials that consumer product companies, and consumers, desire.

Among these new firms is Polystyvert, founded in 2011 by Solenne Brouard Gaillot to tackle polystyrene, one of recycling's tougher challenges. Polystyrene is a notoriously hard-to-recycle material because of its low density—especially in foam form—and its use in contamination-laden applications like food service.

Knowing that polystyrene dissolves in some solvents, Brouard Gaillot tried a Japanese technology based on citrus-derived limonene, but the chemist she hired was unable to replicate the Japanese results. Another chemist directed her to Roland Côté, then a professor at the University of Quebec at Trois-Rivières. Within 3 months, Côté, now Polystyvert's vice president of R&D, hit upon a new solvent, *p*-cymene.

The compound p-cymene is the main constituent of the turpentine that results from the sulfite paper-pulping process. It is also found in cumin and thyme essential oils. It has a relatively high flash point, making it safe to handle. It has a high affinity for polystyrene: up to 40% by weight of the material will dissolve in *p*-cymene. And *p*-cymene won't dissolve other common polymers like polyethylene, polyvinyl chloride, and polyethylene terephthalate.

After Polystyvert dissolves polystyrene, it filters the solution to get rid of foreign materials like wood, paper, and other plastics contaminants. A secondary filtration eliminates smaller particle impurities.

What emerges is a crystal-clear fluid. To that, Polystyvert adds heptane, a dissimilar material that makes the polymer precipitate out of the solution. A distillation step separates the *p*-cymene and heptane and also takes out dissolved small molecules, usually additives in the original compounded polystyrene, like mineral oils and the flame retardant hexabromocyclododecane.

The process recovers 95% of the polystyrene coming in, at a purity of more than 99.9%, the company says. After being turned into pellets again, the polystyrene can be remolded into new products. "All of this is done at low temperatures, so we are

Polystyvert at a glance

» **Launched:** 2011

» **Headquarters:** Montreal

» **Focus:** Plastics recycling

» **Technology:** Solvent purification of polystyrene

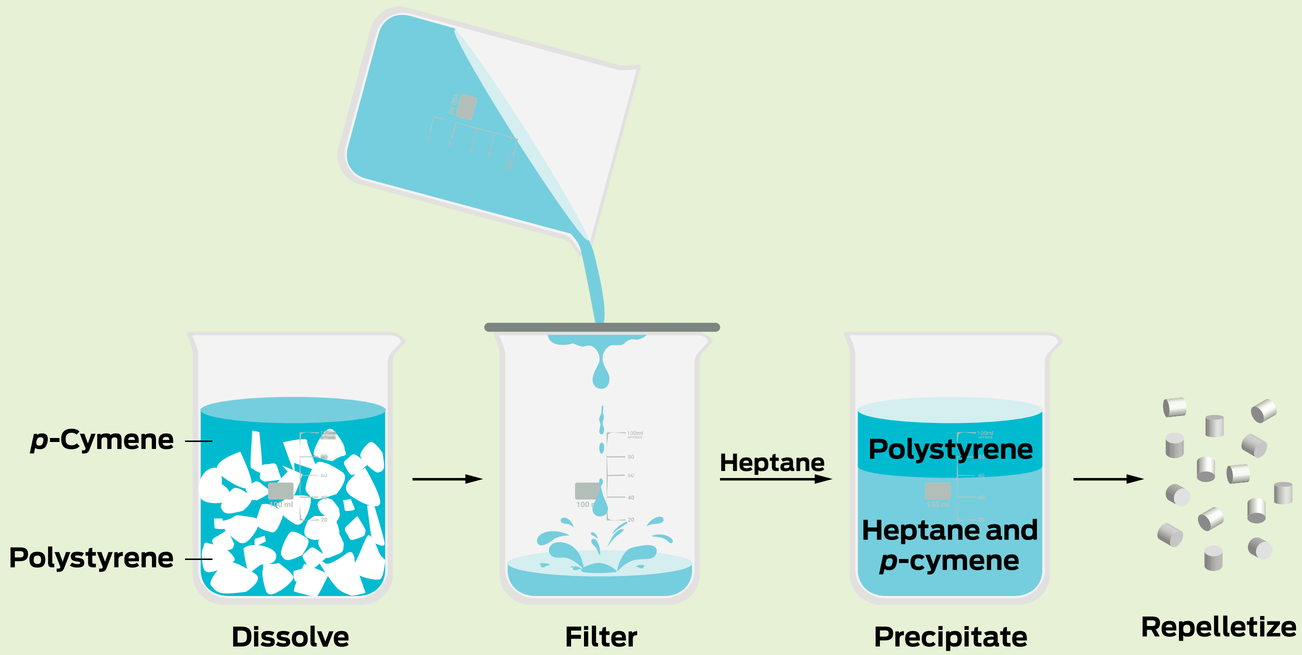
» **Founder:** Solenne Brouard Gaillot

» **Funding or notable partners:** $14 million from Anges Québec, Cycle Capital Management, Energy Foundry, Quadriam Investments, Total, and Transition énergétique Québec

CREDIT: POLYSTYVERT

Purifying polystyrene

Polystyvert's process to purify polystyrene begins by dissolving postconsumer polystyrene in *p*-cymene. Nondissolved impurities, such as foreign metals, plastics, and dirt, are filtered out of the solution. Heptane, in which polystyrene is not soluble, is added to precipitate the polystyrene. The polystyrene is then melted and repelletized so it can be processed into new plastic items.



not consuming much energy," Côté says. The company commissioned a life-cycle analysis that says the process reduces greenhouse gas emissions by 83% versus making virgin materials from fossil fuels. The recycled polystyrene is also 40% cheaper than virgin resin, he says.

Brouard Gaillot sees the low energy consumption as an advantage over other new polystyrene technologies, such as those that depolymerize the material into styrene for repolymerization.

"If you want to implement a circular economy in polystyrene, our technology certainly is very efficient," Brouard Gaillot says. "However, this does not mean that there is no room for depolymerization technology. The issue with plastics is so huge, there are so many things to do, that not only one solution will fix everything."

Polystyvert's technology is generating interest. The company signed a deal with the oil giant and polystyrene maker Total in 2018. "We are very proud to have such a famous partner," Brouard Gaillot says. It has also been working with the styrenic polymer maker Ineos Styrolution.

"If you want to implement a circular economy in polystyrene, our technology certainly is very efficient."

The company raised $8 million from investors in a 2018 funding round. It has brought in nearly $14 million to date, and Brouard Gaillot says it plans to raise another $3 million in 2020.

Polystyvert has been operating a pilot plant with 3 metric tons (t) per day of capacity since June 2018. The firm plans to license its technology for 24 t per day facilities that will be deployed at customer sites. Interested customers include insulation makers that would dissolve polystyrene foam waste from sources such as demolition sites.

Polystyvert has filed for approval with the US Food and Drug Administration for food-contact applications. Brouard Gaillot is confident the firm will win approval because of the unique high-purity product obtained from the *p*-cymene recycling process.

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HOT SHEET

How compatibilizers and other additives could help virgin and recycled plastic work together

Prachi Patel, special to C&EN

When used plastics head for mechanical recycling, they don't come anywhere near full circle. The process makes reuse in original applications challenging because it reduces polymers' molecular weight, diminishing mechanical properties.

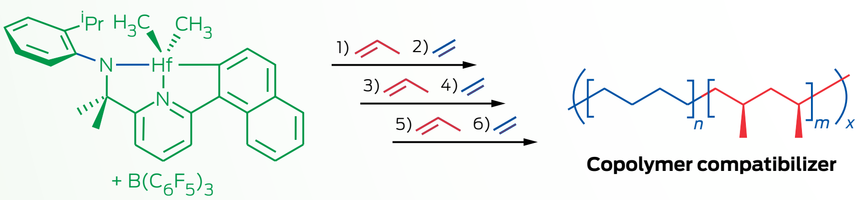
Compatibilizers and other additives could help. Compatibilizers help convert mixed plastic streams and polymer blends into valuable material that can be used on its own or blended with so-called virgin polymers that have never been used. Additives can rebuild polymers' molecular weight and give them virgin-like properties.

Most commonly used polymers are immiscible, says Anne LaPointe, a chemist at Cornell University. Melt two plastics together and they may stay in separate phases, so the resulting material can crack or separate. Compatibilizers interact with different polymers to strengthen their interfacial contact "in the way surfactants stabilize emulsions of oil and water," says Frank Bates, a chemical engineer at the University of Minnesota.

Compatibilizers can work in three ways: molecular entanglement that binds together polymer chains; chemical reactions between functional groups in the polymers; or polar interactions between two polymers. The first two approaches are the most common.

Molecular entanglement is proving useful for compatibilizing polyethylene (PE) and polypropylene (PP), which make up nearly a third of all plastic produced globally. Recyclers find them difficult to separate because of their near-identical densities, Bates says. Chemists could increase the percentage of PE and PP reused by instead helping the polymers work well together.

A hafnium catalyst stitches blocks of polypropylene (red) and polyethylene (blue) together two at a time, yielding the NSF Center for Sustainable Polymers' compatibilizer for the two plastics.



Copolymer compatibilizer

Hafnium catalyst

The compatibilizer that LaPointe, Bates, Cornell's Geoffrey Coates, and their colleagues have developed at the NSF Center for Sustainable Polymers (CSP) is a copolymer. It contains blocks of PE and PP in which the polymer chains are both high molecular weight and highly ordered. In a blend of PE and PP, each block of the copolymer entangles with the chains of the same polymer, bridging the two and stabilizing the mixture.

A pyridylamidohafnium organometallic catalyst stitches the copolymer's blocks of PE and PP together. Adding just 1% by weight of the copolymer to otherwise brittle PE-PP blends makes them mechanically tough. The minimal amount of compatibilizer needed could help offset the cost of the catalyst, according to Bates. A start-up is on the verge of licensing these materials for commercialization.

Dow has also patented a block copolymer for compatibilizing PE and PP, and DuPont developed its own version, called Entira EP. The commercial products require less catalyst per weight of copolymer produced, which is more economical. "But they don't have control over the number and sizes of blocks," LaPointe says. The companies make two blocks compared to the four or more the CSP team can produce. "Having at least four blocks results in greatly improved compatibilization relative to shorter blocks," LaPointe says.

Compatibilizers that employ chemical reactions between functional groups are available for recycling polyolefins with polar functional groups, such as ethylene vinyl alcohol (EVOH) or polyamide (PA). These polymers act as oxygen barriers in flexible packaging. About half of all flexible PE packaging made today has barrier layers, which makes them difficult and expensive to mechanically recycle.

A common approach is to graft an acrylic functional group such as maleic anhydride on PE or PP. The anhydride groups can react with termi-

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Revival

Recyclers can choose compatibilizers or additives to suit specific polymers.

Compatibilizer	Company/Institution	Recycled polymer blends stabilized	Mechanism of action
Entira EP	DuPont	PE-PP	Block copolymer entangles polymers' chains
Fusabond, Elvaloy	DuPont	EVOH-PE, PA-PE, PET-PE	Grafted anhydride groups react with amine or alcohol groups in other polymers
Intune	Dow	PE-PP	Block copolymer entangles polymers' chains
Retain 3000	Dow	EVOH-PE, PA-PE	Grafted anhydride groups react with amine or alcohol groups in other polymers
Unnamed	NSF Center for Sustainable Polymers	PE-PP	Block copolymer entangles polymers' chains
ZeMac Link NP	Vertellus	PET-nylon	Compatibilizer connects terminal amine of nylon with terminal hydroxyl group of PET

Additive	Company	Improves molecular weight and viscosity of	Mechanism of action
Joncryl ADR 4400, Joncryl ADR 4468	BASF	PA, PET	Stitches together acid end groups
Nexamite product line	Nexam Chemical	Nylon, polyesters, polyolefins	Involves temperature-driven chain extenders, branching agents, cross-linkers
ZeMac Extend P	Vertellus	PET	Links PET hydroxyl groups

Sources: Patents, company websites, interviews.
Note: EVOH = ethylene vinyl alcohol, **PA** = polyamide, **PE** = polyethylene, **PET** = polyethylene terephthalate, **PP** = polypropylene

nal amine groups in PA, alcohol groups in EVOH, and hydroxyl end groups in polyethylene terephthalate (PET).

Dow's Retain 3000 compatibilizer—in which a maleic anhydride is grafted on an ethylene-octene polymer—is already in food company Kashi's recyclable packaging for granola. Customers can now put these bags into store drop-off bins that collect PE. "The best use of the modifier is to put it in a package when it is designed and produced," says Jeff Wooster, global sustainability director at Dow Packaging and Specialty Plastics, but plastics processors can also add Retain when creating pellets from recycled barrier film. The company recommends adding 2–15% compatibilizer, depending on the portion of barrier polymer in the film and targeted physical properties.

Meanwhile, multiple firms are developing additives that could rebuild polymers' molecular weight so they can be upcycled into high-value products.

For instance, Lars Öhrn, chief marketing officer for Nexam Chemical, a specialty chemical maker based in Lund, Sweden, says his company makes modifying agents under its Nexamite line that can improve the molecular weight and viscosity of polyolefins, polyesters, and polyamides. They act as chain extenders, branching agents, or cross-linkers.

"Compatibilizers interact with different polymers to strengthen their interfacial contact "in the way surfactants stabilize emulsions of oil and water."

Compatibilizers and additives can add value to recycled materials, but they come with challenges. For one, they have been slow to take off commercially mainly because of expense, Bates says. They work with specific polymer blends; no one-size-fits-all strategy exists. In addition, getting recycled polymer with desired properties requires an optimal amount of compatibilizer, so processors need to know the exact mix of polymers in the waste feed. That works with postindustrial streams. The goal now is to extend this ability to postconsumer waste, which has more unpredictable composition. For recyclers, "the holy grail would be to produce a material that would be superior to the initial compound," Bates says.

HOT SHEET

After setbacks, producers believe the world is finally ready for polyhydroxyalkanoates

ALEX TULLO, C&EN NEW YORK CITY

At Silicon Valley Clean Water in Redwood City, California, an installation assembled from a shipping container, plastic piping, brackets, and a small steel reactor is testing technology that could lead to a more sustainable plastic.

Mango Materials has run this pilot facility since 2015. Raw biogas—which contains methane, carbon dioxide, and hydrogen sulfide—from the water treatment plant bubbles through the reactor. Bacteria in the vessel metabolize the methane into the biopolymer poly(3-hydroxybutyrate), or PHB.

"Once they are the fattest, happiest organisms possible, we have to break open their cells and get the polymer," says Anne Schauer-Gimenez, Mango's vice president of customer engagement. The polymer that Mango extracts—about 250 kg of it per year—is tested in applications such as fibers and packaging for beauty care products.

Mango is among the dozens of firms attempting to create an industry around polyhydroxyalkanoates (PHAs), a class of biodegradable, biobased polymers. Executives with these firms are well aware of Metabolix, now called Yield10 Bioscience, which burned through hundreds of millions of dollars before it failed in PHAs 4 years ago. But Metabolix may have been ahead of its time.

Public awareness of the mounting crisis in plastic waste, especially the plastic that ends up in the oceans, is rising. Governments are imposing bans on single-use plastics, and large consumer product companies are clamoring for solutions. A polymer that can disappear from the environment altogether might just be what the world needs.

PHAs have a lot on their curriculum vitae that suggests they're perfect for this moment. They occur in nature. Bacteria use them to store energy when they lack enough nutrients to reproduce. Scientists have found more than 150 PHAs with different polymer structures. The kind of bacteria and what they are fed—be it sugars, starches, glycerin, triglycerides, or methane—determines the PHA produced.

Biodegradability is the most intriguing property of PHAs. The largest-volume biobased polymer, polylactic acid, also breaks down, but only in an industrial composting facility. PHAs will biodegrade in ambient environments, even an ocean.

> "We're not an iPhone app. Your return doesn't come overnight."

The physical properties of PHAs are often compared with polyolefins such as polyethylene and polypropylene. Indeed, many of the applications that companies have in mind for the polymers—single-use products like food packaging, straws, and cutlery—currently belong to polyolefins. The New Plastics Economy: Rethinking the Future of Plastics, a seminal 2016 report by the Ellen MacArthur Foundation, even lists PHAs as potential substitutes for polyolefins and for polyethylene terephthalate, polystyrene, and polyvinyl chloride.

"There is such a wide array of different PHAs that, depending on what kind of PHA you produce, you can get similar properties to each one of those other materials," says Phil Van Trump, chief technology officer for the PHA developer Danimer Scientific.

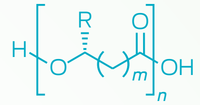
An important distinction in PHAs is between short- and medium-chain polymers. Short-chain PHAs, such as PHB, are made of smaller monomers. Medium-chain PHAs, such as poly(3-hydroxybutyrate-co-3-hydroxyhexanoate), or PHBH, are made of larger ones.

"Pendant chains hanging off your molecule will influence your properties," says Jan Ravenstijn, an independent biopolymer consultant and veteran of the polymer makers DSM and Dow. The short-chain polymers are more crystalline—hard but brittle. The medium-chain ones are tougher and more resilient.

Ravenstijn says PHAs are best suited for applications in which "biodegradation is a must," such as products that "inevitably end up in the environment." He points to slow-release fertilizer coatings made of synthetic polymers like polyurethanes that don't biodegrade.

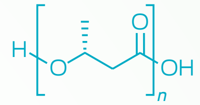
In another such application, the Italian PHA firm Bio-on launched a line of sun creams, called MyKAI, with Unilever in 2019. The creams incorporate micropowders made with Bio-on's PHB that can improve the effectiveness of ultraviolet light–reducing ingredients.

"It is the perfect molecule for that kind of application," Diego Torresan, Bio-on's business development manager, says of PHB. The company makes its PHB from molasses and by-products of

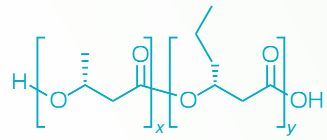


R = alkyl

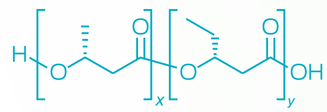
Polyhydroxyalkanoate



Poly-(*R*)-3-hydroxybutyrate (PHB)



Poly(3-hydroxybutyrate-*co*-3-hydroxyhexanoate) (PHBH)



Poly(3-hydroxybutyrate-*co*-3-hydroxyvalerate) (PHBV)

sugar beet production at its demonstration plant near Bologna, Italy. The facility started up in 2018 with 1,000 metric tons (t) of annual capacity, which is dedicated to specialty products such as the powders for Unilever and microbeads for other personal care applications.

Bio-on has been busy developing other PHA applications as well. Late in 2018, it formed a joint venture, Zeropack, with the Italian fruit distributor Rivoira to commercialize PHB packaging for fresh fruit and vegetables. Bio-on is also working on applications such as toys, auto parts, and furniture.

Danimer has PHA technology that it acquired from Procter & Gamble in 2007. The company is already a large compounder of polylactic acid, operating 50,000 t per year of reactive extrusion capacity. Its pilot plant in Bainbridge, Georgia, makes about 10 t of PHAs per month from rapeseed oil.

Van Trump says Danimer's polymer formulation expertise, plus its versatile medium-chain PHA technology, allows it to pursue ambitious applications. For example, with PepsiCo's Frito-Lay division, Danimer has been developing a snack bag material to replace the polypropylene film currently used. It is working on PHA water bottles with Nestlé.

With such heavy interest in their materials, PHA companies are ready to take the next step: commercial plants.

Metabolix made it to this stage a decade ago, and its failure remains a cautionary tale for the rest of the industry. In 2010, the company started up a PHA joint venture with Archer Daniels Midland (ADM) in Clinton, Iowa, that boasted 50,000 t of annual capacity.

ADM shuttered the plant 2 years later because of customers' slow adoption of the materials. The plant couldn't even meet a milestone of 500 t per year of sales, and ADM had to write off $339 million. Metabolix struck out on its own but had to sell its technology to the South Korean firm CJ CheilJedang for $10 million in 2016. It changed focus to agricultural technology and changed its name to Yield10.

"They built too much capacity," Ravenstijn says. "There was no market. And developing a market for a new polymer is something that goes step by step. My advice would always be to build demand ahead of capacity." He believes this is the approach current PHA players are taking.

Bio-on has been developing a market for PHAs since it bought technology for making PHB and other PHAs from the University of Hawaii in 2007. "When we started, the environment was not ready to take on PHA," Torresan says. That's now changed, he says, because of greater customer and brand owner awareness of plastic waste.

He also sees regulatory drivers, such as the European Union's requirement to find by 2021 sustainable alternatives to fossil fuel–based single-use plastic items such as cotton swab sticks, cutlery, plates, and straws. "It is among, if it is not the sole, solution for those kinds of applications," Torresan says of PHAs.

"It's a perfect storm that is brewing," says Van Trump at Danimer. "There is more demand then there was 3 or 5 years ago." The company demonstrated PHA straws in 2018. "Due to the plastics bans and folks not liking paper straws so much, there's a lot of interest," he says.

In Winchester, Kentucky, Danimer has recently completed what it calls the world's largest PHA plant, with capacity of about 8,000 t per year. The $36 million project involved the conversion of an idle algae fermentation facility.

Bio-on's model is not to build large capacity but to license its technology. While its demonstration plant near Bologna is making specialty products for the firm's own sales, it is also meant to prove the process for licensees.

The company has inked a number of PHA licenses. The family-owned company SECI plans to build a 5,000 t per year plant in Italy, and the Russian firm TAIF will build a 10,000 t plant in the Republic of Tatarstan. Bio-on has also licensed its process to companies in France, Spain, and Mexico. These plans may be in doubt, however. The company declared bankruptcy in December, and a court in Bologna is now overseeing its operations.

A few other firms are getting into the business as well. Japan's Kaneka started up a plant with 5,000 t of capacity for PHBH in Takasago, Japan, in December. CJ CheilJedang, with Metabolix's technology in hand, plans to either build a pilot plant or outsource small-scale PHA production, Sim Do Yong, a member of CJ CheilJedang's business development team, tells C&EN. The company aims for commercial production in 2022.

Meanwhile, Mango Materials has nearly completed a demonstration unit at the Redwood City site where it operates the pilot plant. The unit will run continuously and produce more than 100 kg of material per week. "We can derisk a few components of the technology while actually producing meaningful volumes of material to use it for applications," Schauer-Gimenez says.

A commercial plant is still a few years away, she acknowledges. Mango will soon close a fundraising round, Schauer-Gimenez says, with investors who appreciate the amount of time needed to get the technology off the ground.

"Patient capital is what's really key for us right now," she says. "We're not an iPhone app. Your return doesn't come overnight."

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READING LIST

Our picks of the hottest patents and literature on plastic waste and recycling

2020

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» Cano, Israel, Carmen Martin, Jesum Alves Fernandes, Rhys W. Lodge, Jairton Dupont, Francisco A. Casado-Carmona, Rafael Lucena, et al. **"Paramagnetic Ionic Liquid-Coated SiO_2@Fe_3O_4 Nanoparticles—The Next Generation of Magnetically Recoverable Nanocatalysts Applied in the Glycolysis of PET."** *Appl. Catal., B* 260 (Aug. 22, 2019): 118110.

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» Recycling Technologies. **Process and apparatus for treating waste comprising mixed plastic waste.** US Patent 20190010402 (A), filed Sept. 7, 2018, and issued Jan. 10, 2019.

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