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REDUCING PLASTIC'S IMPACT

Advancing Enzymatic Recycling

A deep dive into the investments, patents, and upscaling efforts behind enzymatic plastic recycling

by Anni Schleicher

Plastic waste and its environmental pollution spirals more out of control by the day. Mechanical recycling, the most common technology of its kind, is quickly being complemented by newer methods, such as enzymatic recycling to handle the load.

The enzymatic break down of plastic was first discovered in 2016 when Japanese researchers discovered bacteria isolated from outside a bottle-recycling facility could break down and metabolize plastic.

They found the bacterium Ideonella sakaiensis 201-F6 breaks down plastic by using two enzymes to hydrolyze PET and a primary reaction intermediate, eventually yielding basic building blocks for growth.

Continuing this research in 2018, scientists from the University of Portsmouth, UK revealed an engineered version of one of the enzymes, known as PETase, was able to break down plastic 20% faster than before.

In a 2020 study, the same research team found a "highly synergistic relationship" when mixing PETase with the second enzyme, MHETase, which further doubled plastic bottle digestion.

"We estimate this process can reach cost parity with virgin plastics manufacturing, but at a fraction of the energy input and greenhouse gas emissions," says Dr. Gregg Beckham, co-study author and senior research fellow l-chemical engineering at the National Renewable Energy Laboratory (NREL).

Substantial Commercial Promise

A report co-published by Beckham last September shows the enzymatic recycling process has "substantial promise," as evidenced by a techno-economic analysis, life cycle assessment, and economy-wide modeling.

"We are currently working to identify new enzymes that can attack crystalline PET substrates, as the current enzymes in the literature are not able to do this. Crystalline PET comprises a large percentage of waste PET substrates, like that in bottles and textiles," says Beckham. Some R&D challenges include crystallinity and energy use in particle size reduction. "Separations are also a major cost and energy driver, but there are many good opportunities for innovation there as well," says Beckham. "We are actively looking for industrial partners to work with," he hints.

Enzymatic Recycling Pioneers

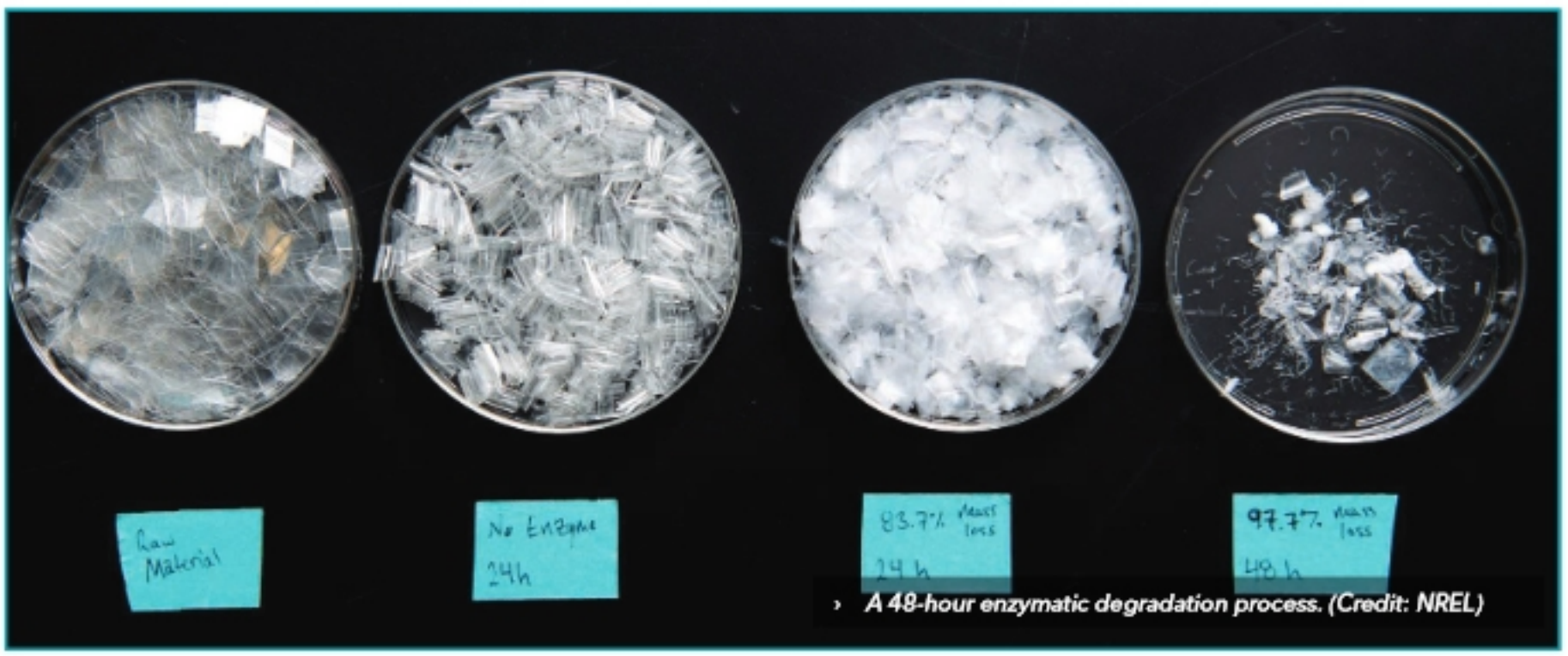
Established in 2011 by Truffle Capital, Carbios is a pioneer in enzymatic recycling. The France-based company aims to provide an industrial solution to PET plastics recycling, the dominant polymer in bottles, trays, and textiles made of polyester.

Carbios' enzymatic recycling technology deconstructs any type of PET waste into its basic components that can then be reused to produce new PET of virgin quality. It has made big strides in its technology over the last years.

Five years ago, Carbios was only able to create some 3% recycled PET plastic in 16 weeks. "Now, [we can achieve] more than 90% degradation in 10 hours. In 2015, we were working at a concentration of PET 10 g per L, but now we are working at 200 to 400 g per L," Professor Alain Marty, chief scientific officer of Carbios, explains.

"In 2015, we were working with a very high quantity of enzymes whereas now we are working with a very small quantity of enzymes, which is less expensive," he details.

By 2025, Carbios aims to



› *A 48-hour enzymatic degradation process. (Credit: NREL)*

› *Bottles created via Carbios' enzymatically recycled plastic. (Credit: Carbios)*

have its first industrial PET recycling production unit operating in Clermont-Ferrand, France. It expects an annual production of 40,000 tons of recycled PET. "This demo plant will prove it will be possible to industrialize this technology. We are confident in this," says Marty.

The company will be exploring sites and conducting engineering studies for the unit until 2022, then begin construction at the end of 2022. By the end of 2024, the unit should complete its start-up, with the first revenues generated in 2025.

FMCG Companies Collaborate

"Our strongest collaborations are with PepsiCo, L'Oréal, Nestlé Waters, Suntory Beverage, and Food Europe. Each of these brand owners make 100% recycled PET bottles with Carbios' biotechnology," says Marty.

To drive a circular economy, PepsiCo has set targets to incorporate recycled PET plastics back into its packaging.

"In addition to current bottle-recycling systems, we are striving to unlock new sources of recycled PET," comments Ron Khan, vice president of beverage packaging at PepsiCo.

"Carbios' technology allows us to use PET materials that would normally go to waste—opaque bottles, trays, textiles. In recovering these materials and using them in our beverage bottles, not only do we unlock further supply, but we also keep such material out of the landfill, reducing the amount of plastic in our environment."

Nestlé unveiled prototypes for its Perrier water bottles based on Carbios' recycling technology in June, while L'Oréal tapped into the tech to launch a cosmetic bottle for its Biotherm brand in 2025.

Critically, Nestlé and PepsiCo rank as top global plastic-polluting companies in the 2021 Brand Audit Report conducted by Break Free From Plastic. PepsiCo has been in the top three plastic polluters every year since 2018. Nestlé ranked fourth in 2021, but was on the podium for the previous three years.

Recycling Down Under

Following in Carbios' footsteps is Samsara Eco, an enviro-tech start-up company based in Australia. Samsara recently developed a technology using plastic-eating enzymes to break plastic down to its core components, which can then be used to recreate brand new plastic.

"We utilize a class of enzymes called hydrolases, which acts as a catalyst to break down polymers into monomers—the building blocks of plastics. The process is still being optimized, but we can go from bottle to monomers in less than an hour in the laboratory," says Professor Colin Jackson, Samsara Eco's chief scientific officer.

In September 2021, Samsara Eco's co-founder Woolworths committed to turning the first 5,000 tons of recycled Samsara plastic into packaging for its house brand products. Starting with the containers used for its mini tomatoes, Samsara packaging is expected to hit Woolworths shelves in the next two years.

Jackson muses: "We've been inspired by Carbios showing what is possible in this space, but also by all of the fundamental academic research on plastic degrading enzymes that dates back many years. We think our process has some exciting differences that will allow us to potentially utilize mixed plastic waste in the future."

UFlex Flexes Its Enzymes

In late 2019, UFlex, one of India's largest flexible plastic packaging companies, introduced Flexzyme, an enzyme-based technology that fully biodegrades polymers through microbial action, moisture, and heat.

The new technology uses a complex of specific plant-based peptides and enzymes, which

is then infused into polyolefins or polyesters to make multilayer plastics.

"Biodegradability and recyclability is an integral part of UFlex's sustainability goals," says Jeevaraj Pillai, UFlex's joint president of flexible packaging, business and new product development. "We strongly believe that all collected waste has to be recycled and the uncollected waste must biodegrade in the littered condition."

"India has quite poor waste collection infrastructure and it will take at least a decade to upscale and fully develop the country's collection infrastructure," he continues. "Enzymatic biodegradation technology would help control the waste in the environment and certainly address the problem of uncollected waste until an adequate setup is ready."

› *Woolworths Group CEO Brad Banducci and Samsara Eco CEO Paul Riley. (Credit: Samsara Eco/Woolworths)*

Power in the Patents

Companies and universities alike continue to invest in enzymatic recycling patents. International patent families (IPFs) represent "high-value inventions," an invention for which patent applications have been filed at two or more patent offices worldwide.

According to the European Patent Office (EPO), top applicants in biological or enzymatic recycling during the 2010 to 2019 period include large companies from diverse industries, mainly chemicals–Dupont and Kaneka Corp (18 IPFs each), Toray Industries and BASF (9 IPFs each), and Roquette Freres (8 IPFs).

But also companies in the food (DSM, Danisco), consumer goods (Procter & Gamble), and automotive sectors (Sumimoto) are listed in the EPO's top applicant list for the same period. The list additionally includes many biotech businesses (Novozymes, Modernatx, Intra Cellular Therapies, Evelo, Carbios Halozyme, Decode Genetics, Codexis) and universities (Harvard University, University of California, Emory University).

Notably, chemical and biological recycling methods accounted for 9,000 EPO-registered IPFs between 2010 and 2019, marking double the number filed for mechanical recycling (4,500 IPFs).

› *Before and after enzymatic degradation. (Credit: Samsara Eco)*

Still at the Research Stage?

Patents for standard chemical methods, such as cracking and pyrolysis, reached a peak in 2014. However, these patents followed closely behind emerging technologies, such as biological methods using living organisms (1,500 IPFs) or plastic-to-monomer recycling (2,300 IPFs).

"We could possibly expect an increase in patent applications, as these [biological and enzymatic recycling] technologies are often still at the research stage," says EPO chief economist Yann Ménière.

"More of them can be expected to reach the industrialization and commercialization stage in the future. In most cases, however, they still have to demonstrate their economic viability."

When asked if biological and enzymatic recycling patents face any major application difficulties, Ménière says the EPO "treats all patent applications the same" regardless of the technology covered. They are subject to the same criteria to receive patent protection and there is no specific difficulty due to the subject matter.

"But it is worth noting that many of these [enzymatic recycling] patent applications still correspond to the upstream research stage, which implies specific challenges for patent applicants due to their longer-term commercialization prospects," says Ménière.

"It is thus important for innovators who file patents in these fields to keep investing in the maintenance and development of their patent portfolio to support future development and commercialization."

Questioning the Coin

Indeed, economic feasibility will be the most challenging part in scaling up enzymatic recycling, flags Dr. Geert Noordzij, R&D manager at Dutch start-up Plantics, with a PhD background in polymer chemistry.

"It depends per class of polymer. That's already a huge distinction that needs to be made in the discussion of recycling to determine the cost per polymer."

Other considerations include enzymes' lifespan, regeneration, and durability. "Enzymes typically need a large water environment and a culture medium to do their job. Afterward, you will have to separate the enzymes from the monomers you obtain. High energy costs and water usage related to this downstream process is probably the biggest bottleneck," he says.