How ‘super-enzymes’ that eat plastics could curb our waste problem

Michael Marshall, 5 Feb 2022

Nudged along by scientists and evolution, micro-organisms that digest plastics have the potential to create an efficient method of recycling

Beaches littered with plastic bottles and wrappers. Marine turtles, their stomachs filled with fragments of plastic. Plastic fishing nets dumped at sea where they can throttle unsuspecting animals. And far out in the Pacific Ocean, an expanse of water more than twice the size of France littered with plastic waste weighing at least 79,000 tonnes.

The plastic pollution problem is distressingly familiar, but many organisations are working to reduce it. Alongside familiar solutions such as recycling, a surprising ally has emerged: micro-organisms. A handful of microbes have evolved the ability to “eat” certain plastics, breaking them down into their component molecules. These tiny organisms could soon play a key role in reducing plastic waste and building a greener economy.

The scale of the problem

As a species, we make an enormous amount of plastic. In 2020, the most recent year for which we have data, 367m tonnes were produced globally, according to trade association Plastics Europe. This represented a slight decline compared with 2019, when 368m tonnes were made, but that was probably because of the Covid-19 pandemic: production had previously increased almost every year since the 1950s. A 2017 study estimated that 8.3bn tonnes of plastic had been made in total.

A huge fraction of this goes to waste. In 2016 the world generated 242m tonnes of plastic waste, according to the World Bank. Despite the popular image, only a small fraction of this ends up in the ocean – but the seas may still be absorbing more than 10m tonnes of plastic every year. As well as the dangers of the plastics themselves, they contain a lot of additives that leach out into the water. “Over time we really don’t know what effects these have,” says Tiffany M Ramos of Roskilde University in Denmark.

Much of the rest ends up in landfills. That does not sound so bad, but a lot of it is single-use plastic, which is inherently wasteful. Making plastic requires extracting fossil fuels such as oil from the ground, with all the pollution risks that entails. Plastic manufacturing also releases greenhouse gases that contribute to global warming. A 2021 report found that the US plastics industry alone releases 232m tonnes of greenhouse gases every year, the equivalent of 116 coal-fired power plants.

The solution is not to stop using plastics altogether, because they are incredibly useful. For example, plastic bottles are far lighter than glass ones, so transporting them requires less energy and releases a smaller amount of greenhouse gases. But we do need a revolution in how we handle plastics, and this is where the micro-organisms come in.

On the scrapheap

In 2016 researchers led by microbiologist Kohei Oda of the Kyoto Institute of Technology in Japan reported a surprise discovery. Oda’s team visited a recycling site that focused on items made of polyethylene terephthalate (PET), a clear plastic that is used to make clothing fibres and drinks bottles.

Like all plastics, PET is a material made up of long string-like molecules. These are assembled from smaller molecules strung together into chains. The chemical bonds in PET chains are strong, so it is long-lasting – exactly what you do not want in a single-use plastic.

Oda's team took samples of sediment and wastewater that were contaminated with PET, and screened them for micro-organisms that could grow on the plastic. It found a new strain of bacterium, called Ideonella sakaiensis 201-F6. This microbe could grow on pieces of PET. Not only that: Oda's team reported that the bacterium could use PET as its main source of nutrients, degrading the PET in the process.

The key to this ability was a pair of enzymes made by the bacteria. Enzymes are complex molecules that can speed up chemical reactions. They are crucial to life: our digestive system relies on enzymes to break down the complex chemicals in food into simpler ones that our bodies can absorb and use. For example, our saliva contains an enzyme called amylase that breaks up the long molecules of starch found in foods such as bread.

Ideonella sakaiensis 201-F6 produces two unique enzymes. The first is a PETase that breaks the long PET molecules down into smaller molecules called MHET. A second enzyme called MHETase then goes to work, producing ethylene glycol and terephthalic acid. These two chemicals are the building blocks of PET, so Ideonella sakaiensis 201-F6 can completely reverse the manufacturing process that made PET.

Plastic eaters

The finding made headlines around the world, but it was not the first example of an organism that could degrade plastics. Reports of plastic-munching microbes date back to at least the early 1990s. The earliest examples were arguably less remarkable, because they could only eat plastics that were chemically flimsy or biodegradable. But by the 2000s researchers had found enzymes that could tackle tougher plastics.

A prominent researcher in this area has been Wolfgang Zimmermann of Leipzig University in Germany. His team studied enzymes called cutinases, which it obtained from bacteria such as Thermobifida cellulosilytica, and which could also break down PET.

Lars Blank of Aachen University in Germany first heard about this in 2012. He set about creating a consortium of researchers to study plastic-eating enzymes. This became the P4SB project, which ran from 2015 to 2019. Blank has since set up a project called MIX-UP, which sees European and Chinese researchers cooperating.

By the mid-2010s plenty of plastic-degrading enzymes were known. The potential was clear to Gabriella Caruso of the Institute for Coastal Marine Environment in Messina, Italy, who wrote in a 2015 review that "microbial degradation of plastic is a promising eco-friendly strategy which represents a great opportunity to manage waste plastic materials with no adverse impacts".

So why did Ideonella sakaiensis 201-F6 cause such a stir? "The difference with the 2016 paper was this micro-organism could use the plastic as its sole energy and food source," says John McGeehan of the University of Portsmouth. "That's actually quite surprising and it kind of shows evolutionary pressure in action. If you're the first bacterium in that rubbish pile that suddenly has a taste for plastic, then you've got an unlimited food source."

Put another way, the earlier enzymes had not evolved for plastics. They evolved to break down tough chain molecules found in living things, and their ability to degrade plastic was a side-effect. In contrast, the enzymes in Ideonella sakaiensis 201-F6 were specialised.

Blank has a different interpretation, arguing that the Ideonella sakaiensis 201-F6 enzymes are not especially good because they only degrade PET slowly. "Wolfgang Zimmermann had far better enzymes at that point," he says. But the excitement the paper created had a huge impact. "Suddenly the media and also the academic literature really cranked up and a lot of interest came in."

Better and better enzymes

Two years later McGeehan and his colleagues took things further. They produced a three-dimensional structure of the Ideonella sakaiensis 201-F6 PETase, shedding light on how it worked. Hoping to understand how it evolved, they tweaked the structure. To their surprise, this made the enzyme more efficient at degrading PET. Clearly, it was possible to improve the enzyme.

McGeehan now wants to take that further, modifying the PETase and other such enzymes so that they can be used on an industrial scale to break down plastics that would otherwise linger in the environment. "We've got a big £6m grant from the government," he says, and they have started a specialist institute called the Centre for Enzyme Innovation.

This is now bearing fruit. In 2020 McGeehan's team reported that it had linked the PETase and MHETase enzymes together. This "super-enzyme" could eat PET about six times faster than the two enzymes working separately. Other groups such as Blank's MIX-UP have produced modified enzymes of their own.

Meanwhile there is evidence that microbes all around the world are evolving similar abilities. A study published in October 2021 looked at microbial DNA from a range of habitats. In areas with high levels of plastic pollution, the researchers found that the microbes were more likely to have enzymes with plastic-degrading tendencies. In line with this, a 2020 study identified a soil bacterium that can feed on some of the components of polyurethane, which releases toxic chemicals when it breaks down.

The question now becomes: how significant a role can these enzymes really play in reducing plastic pollution?

The circular economy

So far, most of the activity has been in universities, but some groups are attempting to commercialise the technology. The University of Portsmouth has set up Revolution Plastics, which aims to forge links between academics and industry. "We've already advertised a joint PhD project with Coca-Cola," says McGeehan. He is also part of an international research team called BOTTLE, which is negotiating with large companies.

The most advanced project is run by Carbios, a French biotechnology company. In September 2021 it opened a pilot plant in Clermont-Ferrand, where it will test a system for recycling PET. Carbios's system uses an enzyme that was first identified in compost, which they modified so that it worked faster and could operate at high temperatures where PET is softer.

The advantage of these enzymes is that they break down the plastic at the molecular level, so it is possible to recreate the highest-quality plastic. In contrast, other forms of recycling cause a slow decline in quality, until eventually the plastic cannot be recycled again and gets landfilled or incinerated. Enzymatic recycling, in theory at least, is truly circular. "That's what we call a closed-loop recycling system," says Ramos. "You recycle something, but then you're able to make something new of the same quality out of that." To date, only a tiny percentage of plastics are being recycled in this way, but the enzymes could change that – "Which would be great."

McGeehan says: "I think in the next five years we're going to be seeing demonstration plants all over the place."

Still, there are limits to the enzymes' usefulness. "It will never be a one-size-fits-all type of solution," says Ramos, and we should not count on the enzymes to mop up all our plastic waste. Some plastics are even tougher than PET.

Blank points out that the enzymes work best if the plastic has been softened by heating. That means releasing the enzymes into the environment would not do much good: they only really work in temperature-controlled reactors. So the solution to plastic in the sea remains the same as before: we have to stop releasing it in the first place.

Nevertheless, it seems likely that plastic-eating enzymes will have a role to play as societies move towards a circular economy in which everything is recycled as much as possible. In a study published in July 2021, McGeehan and his colleagues estimated how much enzymatic recycling of PET will cost. They calculate that it could compete on cost with standard manufacturing methods, which use fossil fuels as feedstock.

A cleanup operation on a beach covered in nurdles in May

The key is to be savvy about where we use the enzymes, says Blank. Some plastics can be mechanically recycled, a technology that is improving rapidly, so they probably are not the best targets. Instead, he says, researchers should go for plastics that cannot be recycled any other way – particularly if they can become substances that are otherwise expensive to make.

Ultimately, the enzymes have to be part of a revolution in the entire way we make and use plastics, says Ramos. Better methods of recycling are useful, she adds, but they are only part of the solution. It is also important for plastic products to be designed in such a way that they can easily be reused and recycled. That might mean avoiding designs that use several kinds of plastic, or fuse plastic with other materials, as these are very difficult to recycle.

As with all our environmental problems, there is no silver enzyme. These chemical machines can help us recycle plastic better, but we will always need to pick up our litter.