Recycling has a flaw — could mutant bacteria be the answer?

When researchers in Japan found a microbe that could break down old bottles, they began hunting for other plastic predators able to devour waste on an industrial scale, **Tom Whipple** reports

No one will ever know quite how it happened, or exactly when. But here is one plausible explanation for how bacteria in a Japanese recycling plant started eating plastic. Each day, plastic bottles piled up in the plant in Osaka, ready to be filtered, separated, recycled and reused. A few bacteria lived among this casually tossed detritus, surviving mainly on the sugary remnants of fizzy drinks left sloshing around in the bottles. It was an energy-poor environment — but the strange thing is, there was energy all around waiting to be unlocked.

It had taken energy to make those plastic bottles and this remained within their chemical bonds. Nature, though, had no way of unlocking it. How could it? In the span of evolutionary time, plastic has only just been invented.

The great tragedy of plastic is that this wonder material is destined to go brittle, fragment, degrade and become useless, but never decompose.

Except, on one ordinary day, in this one ordinary place in Japan, one piece of plastic did decompose. A bacterium had reproduced with a slight mutation, meaning the chemical tools its offspring used to eat things behaved slightly differently.

The bacterium had evolved to use an enzyme that ordinarily broke down the bonds of polymers — long strings of repeating molecules — found in plants. However, this enzyme had now started to break the bonds of polymers found in plastics, and so, in essence, the bacterium could eat plastic.

And if you get a microbe that can eat plastic in an environment where almost all of the potential nutrition is plastic? "That microbe is going to be the king," says Shosuke Yoshida, a research associate at Kyoto University.

Years after that bacterium became the microbial monarch of the Osaka recycling plant, its descendants had indeed started to conquer the world. It was everywhere in Osaka, an unstoppable rise fuelled by its new food source.

That was when Yoshida turned up, took a little bit of soil and put it in a test tube to see what happened.

Yoshida, as is traditional for junior laboratory members the world over, had been given a time-consuming, tedious and probably pointless job. Roaming around Japan, from hot springs to parks, he had been taking soil samples, sloshing them in test tubes with bits of plastic, hoping they would eat it, and watching as nothing happened.

"Every day it was very boring and there was no success," he says. This was not what he thought science should be. "There was no DNA work, no protein work, just looking for microbes — and these microbes we wanted maybe existed nowhere on the Earth."

Then, Yoshida returned with the Osaka sample and his job was boring no longer. The microbes ate the plastic in his test tube, which was polyethylene terephthalate (PET), the type used to make most disposable bottles. "We were very surprised, very excited. We had doubt, though. We couldn't believe it."

He was not the only one given this task. Unbeknown to Yoshida, other researchers with similar PhD supervisors were sent to nooks and crannies to take samples and find microbes. They, too, found the job tedious and pointless. Until, through the kind of serendipity that only comes with methodical persistence, they found — with another microbe entirely — that it wasn't. In Yoshida's test tube and the flurry of research that followed, did we at last hold the solution to the world's plastic problems?

THE PROBLEM WITH RECYCLING

It is, in general, wrong to say that most single-use plastic is recycled, even when we put it in the right bin. A better term is "downcycled". Each year, the world produces about 400 million tonnes of plastic. This is roughly the same as the mass of humans on Earth.

Of that figure, 19 per cent, very roughly, will be incinerated — producing noxious black smoke.

About half of the plastic produced goes to sanitary landfills, where the waste is isolated from the environment until it has completely degraded and is considered safe.

About 22 per cent is disposed of in uncontrolled dumpsites, burnt in open pits or leaked into the environment. Some plastic waste might find fame: the plastic bag that photogenically suffocates a turtle or the microplastic tracked down by scientists on the summit of Everest. Most will just splinter and crumble to form a new layer of sediment for our new geological epoch: the anthropocene.

The other 9 per cent, though, has an apparently happier end. It will be taken by diligent consumers and put where it should be: in the recycling bin, to be turned back into bottles and bags and all the things that keep our modern economy going.

Except it won't be. Not really.

Plastic is a polymer. It is made from long chains of repeating chemical building blocks called monomers. What makes plastic wonderful is that these polymers can be shaped and moulded into whatever you want.

The problem is that once that has happened, there is no easy way to regain the original monomers, join them together and do it all again. Plastic bottles can be shredded and melted and pressed back into shape but the polymers in this recycled plastic will be shorter and the plastic less pure. What was once clear virgin plastic will become grey and more brittle.

Each time plastic goes through this process it becomes less valuable and can be used in fewer products. Eventually, everything becomes carpet. And not even nice carpet.

"There are these huge warehouses full of textiles that no one knows what to do with," says John McGeehan, who leads a research team on enzyme engineering at the University of Portsmouth. "It's all on a trajectory downwards to landfill or incineration, it's just a matter of time." What, though, if we had a way not just to get rid of that plastic, but to return it to its original state by extracting the monomers that can become the polymers? In that scenario, we would have a plastic waste resource rather than a problem.

McGeehan remembered when he first heard about the bacterium in the Osaka recycling plant. He had been working on an international collaboration looking at how enzymes broke down natural polymers. Then he got a call from one of his collaborators. "He said, 'Oh my God, have you seen this paper?' It was amazing. It wasn't living off the sugary waste, it was living off the plastic itself."

His colleague asked him if he had funding they could redirect to work on it. "I said, 'No, do you?' He said, 'No, but let's do it anyway'. We threw everything at it. Who knew that five years later we would have a £10 million centre and 30 people working on it?"

They needed the research project because the plastic-eating enzyme the bacterium made wasn't ready. It was fine for a bacterium wanting to sustain itself, not so much for industrial scale.

What happened in Osaka was the first evolutionary step into the new biological niche of plastic, the enzyme

The litter-picking Forrest Gump blazing a trail on our beaches

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PHOTOGRAPHS: MARTIN POPE FOR THE TIMES

Luke Douglas-Home at Hunstanton, Norfolk. He has so far also been through Lincolnshire and the East Riding of Yorkshire, and will tackle North Yorkshire next

> A near-death experience led him to use running as a form of recovery — and along the way he has cleared 100kg of plastic from the coast

About two thirds of the way into the 1994 film *Forrest Gump*, the eponymous hero gets off his porch bench and starts running "for no particular reason" — other than being heartbroken (Blanca Schofield writes). What starts as a jog to the end of the road becomes a journey through his town, then his county and then across America. Now the UK has its own Forrest, although ours has an explicit reason for running: a compulsion to combat the plastic waste polluting our beaches. "A couple of people have made that reference [to *Forrest Gump*]," says Luke Douglas-Home. "Maybe that's the crux of what I'm doing, although rather than upset, I'd say I have restrained anger."

Fed up with the "plasticisation" of the oceans and the "pledge-ridden" politicians yet to tackle it, the 51-year-old father of two has taken matters into his own hands by embarking on a litter-picking run along the UK's coastline. Running 12 to 18 miles once or twice a week since November 1, the "coastline runner", as he has been dubbed in the local press, has so far covered Norfolk, Lincolnshire and the East Riding of Yorkshire, and will tackle North Yorkshire next in September. Aside from collecting coastal litter, of which he has amassed about 100kg, he writes reports on the local waste infrastructure with the help of the environment department and the Environment Agency.

Though this is a testing feat, he has always been a keen runner. This became particularly true after a horse riding accident in Romania in 2005, which left him in a coma and paralysed on his right side, and he was told that his rehabilitation depended on physical exercise. "I've made this amazing recovery and that's largely down to running," Douglas-Home says. The near-death experience was also what led him to leave his career in cultural conservation for one in environmental sustainability. "The physical recovery showed me the possibility that you can change things for the better," he says. In 2015 he set up A Future Without Rubbish, which successfully campaigned to ban the plastic stirrer in 2020.

Despite this, Douglas-Home says that banning plastics is the wrong approach, stressing the need to make the alternative economically attractive. It is also not enough to rely on individuals' behaviour, he says, which is why he has kept a close dialogue with local councils and will give advice to the Crown Estate on how it can better manage waste on its land. "I hope this enables … systemic change in the main landlords of the coast."

equivalent of that first air-breathing fish that, hundreds of millions of years ago, flopped on to a beach. What they needed, to recycle at scale, was something far more advanced: a *tyrannosaurus rex* of plastic.

THE T REX OF PLASTIC

McGeehan and his collaborators needed it to work faster and, ideally, to be adapted to greater heat. At 70C, a plastic bottle begins to melt, losing the rigid structure that made the plastic so desirable. When that happens enzymes work much faster — perhaps 100 times faster. If, that is, you have enzymes which can survive at that temperature. The Osaka enzyme couldn't.

Since the publication of that original paper by Yoshida and his colleagues, McGeehan and his own collaborators have taken the work on, along with other groups around the world. They have tweaked the enzyme to make it work faster and have worked to improve its "thermal stability". They have also gone looking for others. There is a reason, McGeehan says, that the bacteria can evolve this ability. "So many bacteria live on plant matter. Any green leaves, for instance, have a waxy coating on them called cutin, and that's nature's polyester," says McGeehan. To eat it, they need to break its bonds. "So they've not evolved to eat plastic, but they've got the chemistry there already."

If this is true, this would mean there are many other such enzymes — and it seems that there are. A little under a decade after Yoshida found his enzyme, but four years before he published the results, another was found, again in Japan, this time amid leaf litter. In the middle of a hot, decomposing compost heap, bacteria were evolving enzymes that could break down cutin, but now at high temperatures. It went unnoticed until, in 2015, a French team spotted its potential. This enzyme hadn't adapted for plastic, but it was so good at dealing with nature's polyester that it didn't matter. It could decompose cutin, and it could decompose plastic too.

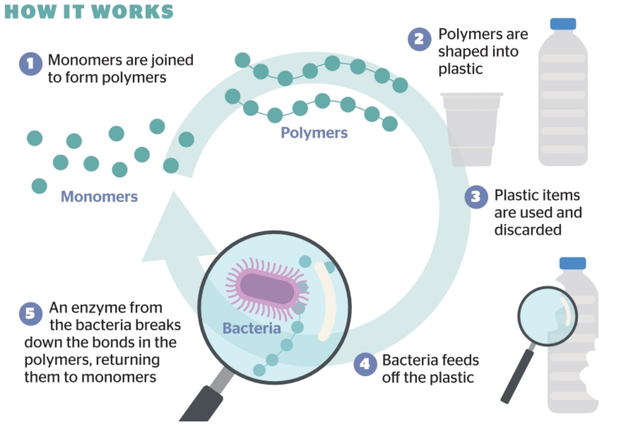
Alain Marty, then at the University of Toulouse, began working on the new enzyme. To go into cutin and chomp through its bonds, it had evolved a particular shape. To more efficiently chomp through the bonds of plastic — to get in between the monomers and tease them apart — it needed to morph into something else.

Given time, this would happen. "Over millions of years, faced with the new problem of plastic, it would get better and better at degrading it," says Marty. They liked to view what they did as helping this process on its way. They determined the three-dimensional structure of the protein, then, using computer modelling, they tweaked the active site.

"We did this evolution not in a million years but in two years — to obtain a very, very good enzyme," Marty says. It is good enough that it caught the attention of Coca Cola and L'Oréal. Marty is now chief scientific officer of Carbios, a company that has commercialised the technology. In three years, they are on course to have a recycling plant — a true recycling plant — with an annual capacity of 50,000 tonnes of plastic a year.

"Plastic," says Marty, "is fantastic. It is waste that is a catastrophe." If this works, however, then "it is no longer waste, it is a resource". After converting the polymer to monomers, they will send these monomers to a plastic plant, where they will be made into fresh polymers again.

HOW IT WORKS



THE SEARCH IS ON

This plant, however, and the others that will follow, with other enzymes, is not the solution. Not yet. PET, of which most plastic bottles are made, has a particular kind of bond between its monomers that can be cut using a specialised enzyme. There are other plastics, though — 80 per cent of them, in fact — that have other, tougher, bonds that remain impervious and which need their own enzymes.

Even if we find the *tyrannosaurus rex* of PET, we need more plastic predators. Scientists are increasingly confident, however, that they are out there. To find a plastic-chomping bacterium once could be sheer luck. To find one twice? That's different.

Other enzymes — better enzymes still — must be out there and, across the world, people are looking. They are burying plastics in soil, swabbing in the springs of Yellowstone, sieving the detritus of recycling plants, searching through the genomes of known species.

McGeehan has a particular favourite hunting ground: mangrove forests. For millions of years, the humid roots have been a perfect ecosystem for wood-eating bacteria that break down the polymer lignin.

In recent years, though, another polymer has arrived in the forests: plastic that has found its way into the Amazon, Yangtze and Mekong rivers, and from there to the sea.

Eventually, this plastic — toothbrushes and fishing nets, cotton buds and Lego pieces — comes to rest, a brightly coloured harvest caught among the mangroves. The first lignin-eating bacterium that switches to being a toothbrush-eating bacterium will become king of the mangroves.

In the past decades we have realised that one of the very things that makes plastic so useful, its durability, is also its great flaw.

In our plastic bags, our bottles and our discarded toys lies an ecological disaster. There also, though, lies a new biological niche.

If evolution has taught us anything it is that if there is a new foodstuff, nature will find a way to eat it. In evolutionary time, it is inevitable that plastic will become just another part of the food chain. Humans do not have the luxury of evolutionary time.

Somewhere, perhaps in the great Pacific garbage patch, perhaps amid the roots of a once-pristine mangrove forest, perhaps even in the geysers of Yellowstone, a bacterium is finding a way to exploit plastic, and to do so better and more reliably. Now we need to find it.