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Microplastics collected from the Magothy River in Maryland.

MICROPLASTICS ARE EVERYWHERE — BUT ARE THEY HARMFUL?

Scientists are rushing to study the tiny plastic specks that are in marine animals – and in us.

By XiaoZhi Lim

Dunzhu Li used to microwave his lunch each day in a plastic container. But Li, an environmental engineer, stopped when he and his colleagues made a disturbing discovery: plastic food containers shed huge numbers of tiny specks – called microplastics – into hot water. "We were shocked," Li says. Kettles and baby bottles also shed microplastics, Li and other researchers, at Trinity College Dublin, reported last October[1]. If parents prepare baby formula by shaking it up in hot water inside a plastic bottle, their infant might end up swallowing more than one million microplastic particles each day, the team calculated.

What Li and other researchers don't yet know is whether this is dangerous. Everyone eats and inhales sand and dust, and it's not clear if an extra diet of plastic specks will harm us. "Most of what you ingest is going to pass straight through your gut and out the other end," says Tamara Galloway, an ecotoxicologist at the University of Exeter, UK. "I think it is fair to say the potential risk might be high," says Li, choosing his words carefully.

Researchers have been worried about the potential harms of microplastics for almost 20 years – although most studies have focused on the risks to marine life. Richard Thompson, a marine ecologist at the University of Plymouth, UK, coined the term in 2004 to describe plastic particles smaller than 5 millimetres across, after his team found them on British beaches. Scientists have since seen microplastics everywhere they have looked: in deep oceans; in Arctic snow and Antarctic ice; in shellfish, table salt, drinking water and beer; and drifting in the air or falling with rain over mountains and cities. These tiny pieces could take decades or more to degrade fully. "It's almost certain that there is a level of exposure in just about all species," says Galloway.

The earliest investigations of microplastics focused on microbeads found in personal-care products, and pellets of virgin plastic that can escape before they are moulded into objects, as well as on fragments that slowly erode from discarded bottles and other large debris. All these wash into rivers and oceans: in 2015, oceanographers estimated there were between 15 trillion and 51 trillion microplastic particles floating in surface waters worldwide. Other sources of microplastic have since been identified: plastic specks shear off from car tyres on roads and synthetic microfibres shed from clothing, for instance. The particles blow around between sea and land, so people might be inhaling or eating plastic from any source.

From limited surveys of microplastics in the air, water, salt and seafood, children and adults might ingest anywhere from dozens to more than 100,000 microplastic specks each day, Albert Koelmans, an environmental scientist at Wageningen University in the Netherlands, reported this March[2]. He and his colleagues think that in the worst cases, people might be ingesting around the mass of a credit card's worth of microplastic a year.

Regulators are taking the first step towards quantifying the risk to people's health – measuring exposure. This July, the California State Water Resources Control Board, a branch of the state's environmental protection agency, will become the world's first regulatory authority to announce standard methods for quantifying microplastic concentrations in drinking water, with the aim of monitoring water over the next four years and publicly reporting the results.

Evaluating the effects of tiny specks of plastic on people or animals is the other half of the puzzle. This is easier said than done. More than 100 laboratory studies have exposed animals, mostly aquatic organisms, to microplastics. But their findings – that exposure might lead some organisms to reproduce less effectively or suffer physical damage – are hard to interpret because microplastics span many shapes, sizes and chemical compositions, and many of the studies used materials that were quite unlike those found in the environment.

The tiniest specks, called nanoplastics – smaller than 1 micrometre – worry researchers most of all (see 'Microplastics to scale'). Some might be able to enter cells, potentially disrupting cellular activity. But most of these particles are too small for scientists even to see; they were not counted in Koelmans' diet estimates, for instance, and California will not try to monitor them.

One thing is clear: the problem will only grow. Almost 400 million tonnes of plastics are produced each year, a mass projected to more than double by 2050. Even if all plastic production were magically stopped tomorrow, existing plastics in landfills and the environment – a mass estimated at around 5 billion tonnes – would continue degrading into tiny fragments that are impossible to collect or clean up, constantly raising microplastic levels. Koelmans calls this a "plastic time bomb".

"If you ask me about risks, I am not that frightened today," he says. "But I am a bit concerned about the future if we do nothing."

Modes of harm

Researchers have several theories about how plastic specks might be harmful. If they're small enough to enter cells or tissues, they might irritate just by being a foreign presence – as with the long, thin fibres of asbestos, which can inflame lung tissue and lead to cancer. There's a potential parallel with air pollution: sooty specks from power plants, vehicle exhausts and forest fires called PM_{10} and $PM_{2.5}$ – particulate matter measuring 10 μm and 2.5 μm across – are known to deposit in the airways and lungs, and high concentrations can damage respiratory systems. Still, PM_{10} levels are thousands of times higher than the concentrations at which microplastics have been found in air, Koelmans notes.

The larger microplastics are more likely to exert negative effects, if any, through chemical toxicity. Manufacturers add compounds such as plasticizers, stabilizers and pigments to plastics, and many of these substances are hazardous – for example, interfering with endocrine (hormonal) systems. But whether ingesting microplastics significantly raises our exposure to these chemicals depends on how quickly they move out of the plastic specks and how fast the specks travel through our bodies – factors that researchers are only beginning to study.

Another idea is that microplastics in the environment might attract chemical pollutants and then deliver them into animals that eat the contaminated specks. But animals ingest pollutants from food and water anyway, and it's even possible that plastic specks, if largely uncontaminated when swallowed, could help to remove pollutants from animal guts. Researchers still can't agree on whether pollutant-carrying microplastics are a significant problem, says Jennifer Lynch, a marine biologist affiliated with the US National Institute of Standards and Technology in Gaithersburg, Maryland.

Perhaps the simplest mode of harm – when it comes to marine organisms, at least – might be that organisms swallow plastic specks of no nutritional value, and don't eat enough food to survive. Lynch, who also leads the Center for Marine Debris Research at Hawaii Pacific University in Honolulu, has autopsied sea turtles that are found dead on beaches, looking at plastics in their guts and chemicals in their tissues. In 2020, her team completed a set of analyses for 9 hawksbill turtle hatchlings, under 3 weeks old. One hatchling, only 9 centimetres long, had 42 pieces of plastic in its gastrointestinal tract. Most were microplastics.

"We don't believe any of them died specifically from plastics," Lynch says. But she wonders whether the hatchlings might have struggled to grow as fast as they need to. "It's a very tough stage of life for those little guys."

Marine studies

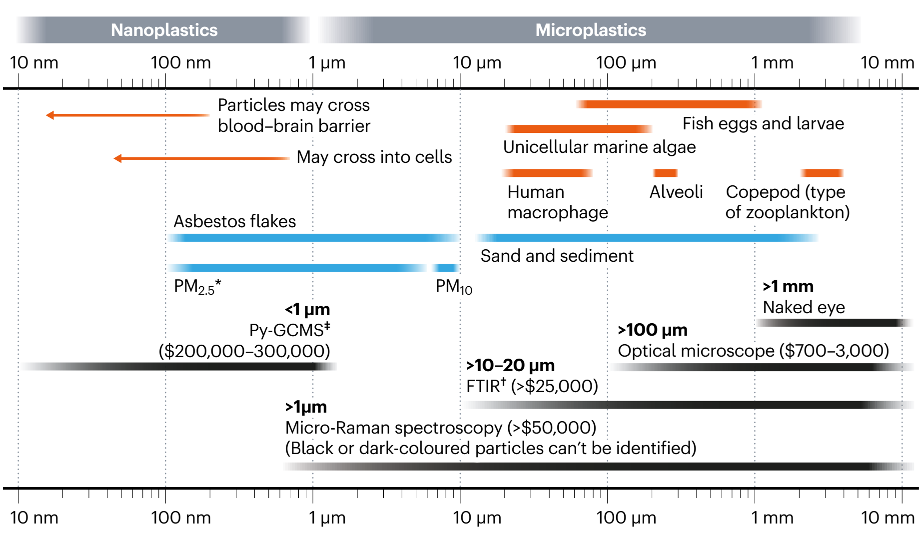
Researchers have done the most work on microplastic risks to marine organisms. Zooplankton, for instance, among the smallest marine organisms, grow more slowly and reproduce less successfully in the presence of microplastics, says Penelope Lindeque, a marine biologist at the Plymouth Marine Laboratory, UK: the animals' eggs are smaller and less likely to hatch. Her experiments show

"It's almost certain that there is a level of exposure in just about all species."

MICROPLASTICS TO SCALE

Micro- and nanoplastics are of similar size to many biological organisms, and become harder and more expensive to analyse as they get smaller.

Biological objects
Non-biological particles
Tools for analysis

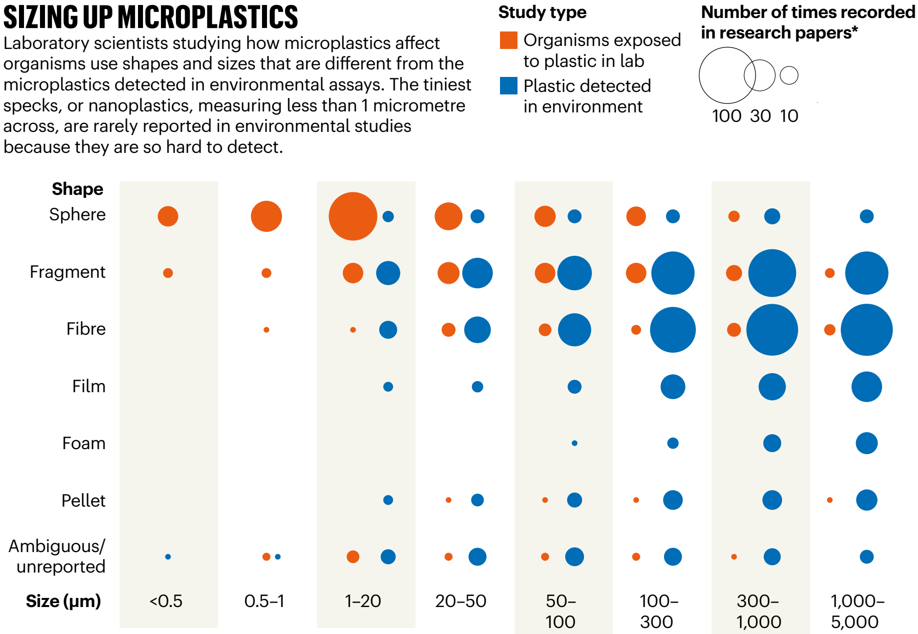


*Particulate matter less than 2.5 micrometres ($PM_{2.5}$) or less than 10 μm (PM_{10}) in diameter, often from soot, vehicle exhaust or dust; †FTIR, Fourier-transform infrared spectroscopy; ‡Py-GCMS, pyrolysis–gas chromatography–mass spectrometry.

SOURCE (TOOLS AND COSTS): S. PRIMPKE *ET AL. APPL. SPECTROSC.* **74**, 1012–1047 (2020).

SIZING UP MICROPLASTICS

Laboratory scientists studying how microplastics affect organisms use shapes and sizes that are different from the microplastics detected in environmental assays. The tiniest specks, or nanoplastics, measuring less than 1 micrometre across, are rarely reported in environmental studies because they are so hard to detect.



*Nature analysis of 136 detection and 159 exposure studies.

SOURCE: NATURE ANALYSIS

that the reproduction problems stem from the zooplankton not eating enough food[3].

But, because ecotoxicologists started running experiments before they knew what kinds of microplastics exist in aquatic environments, they depended heavily on manufactured materials, typically using polystyrene spheres of smaller sizes and at concentrations much higher than surveys found (see 'Sizing up microplastics').

Scientists have started shifting to more environmentally realistic conditions and using fibres or fragments of plastics, rather than spheres. Some have started coating their test materials in chemicals that mimic biofilms, which appear to make animals more likely to eat microplastics.

Fibres seem to be a particular problem. Compared with spheres, fibres take longer to pass through zooplankton, Lindeque says. In 2017, Australian researchers reported that zooplankton exposed to microplastic fibres produced half the usual number of larvae and that the resulting adults were smaller. The fibres were not ingested, but the researchers saw that they interfered with swimming, and identified deformations in the organisms' bodies[4]. Another study[5] in 2019 found that adult Pacific mole crabs (*Emerita analoga*) exposed to fibres lived shorter lives.

Most laboratory studies expose organisms to one type of microplastic, of a specific size, polymer and shape. In the natural environment, organisms are exposed to a mixture, says Koelmans. In 2019, he and his doctoral student Merel Kooi plotted the abundances of microplastics reported from 11 surveys of oceans, rivers and sediment, to build models of mixtures in aquatic environments.

Last year, the two teamed up with colleagues to use this model in computer simulations that predict how often fish would encounter microplastics small enough to eat, and the likelihood of eating enough specks to affect growth. The researchers found that at current microplastic pollution levels, fish run that risk at 1.5% of locations checked for microplastics[6]. But there are likely to be hotspots where the risks would be higher, says Koelmans. One possibility is the deep sea: once there, and often buried in sediment, it is unlikely the microplastics will travel elsewhere and there is no way to clean them up.

The oceans already face many stressors, which makes Lindeque more afraid that microplastics will further deplete zooplankton populations than that they will transfer up the food chain to reach people. "If we knock out something like zooplankton, the base of our marine food web, we'd be more worried about impacts on fish stocks and the ability to feed the world's population."

Human studies

No published study has yet directly examined the effects of plastic specks on people, leading researchers say. The only available studies rely on laboratory experiments that expose cells or human tissues to microplastics, or use animals such as mice or rats. In one study[7], for instance, mice fed large quantities of microplastics showed inflammation in their small intestines. Mice exposed to microplastics in two studies had a lowered sperm count[8] and fewer, smaller pups[9], compared with control groups. Some of the *in vitro* studies on human cells or tissues also suggest toxicity. But, just as with the marine studies, it's not clear that the concentrations used are relevant to what mice – or people – are exposed to. Most of the studies also used polystyrene spheres, which don't represent the diversity of microplastics that people ingest. Koelmans also points out that these studies are among the first of their kind, and could end up being outliers once there's an established body of evidence. There are more *in vitro* studies than animal studies, but researchers say they still don't know how to extrapolate the effects of solid plastic specks on tissues to possible health problems in whole animals.

One question surrounding risk is whether microplastics could remain in the human body, potentially accumulating in some tissues. Studies in mice have found that microplastics around 5 µm across could stay in the intestines or reach the liver. Using very limited data on how quickly mice excrete microplastics and the assumption that only a fraction of particles 1–10 µm in size would be absorbed into the body through the gut, Koelmans and colleagues estimate that a person might accumulate several thousand microplastic particles in their body over their lifetime[2].

Some researchers have started to explore whether microplastics can be found in human tissue. In December, a team documented this for the first time in a study that looked at six placentas[10]. Researchers broke down the tissue with a chemical, then examined what was left, and ended up with 12 particles of microplastic in 4 of those placentas. Yet it's not impossible that these specks were the result of contamination when the placentas were collected or analysed, says Rolf Halden, an environmental-health engineer at Arizona State University in Tempe – although he commends the researchers for their efforts to avoid contamination, which included keeping delivery wards free of plastic objects, and for showing that a control set of blank materials taken through the same sample analysis was not contaminated. "There is a continuing challenge of demonstrating conclusively that a given particle actually originated in a tissue," he says.

Those who are worried by their microplastic exposure can reduce it, says Li. His work on kitchenware found that the amounts of plastic shed depend highly on temperature – which is why he's stopped microwaving food in plastic containers. To reduce issues with baby bottles, his team suggests that parents could rinse sterilized bottles with cool water that has been boiled in non-plastic kettles, so as to wash away any microplastics released during sterilization. And they can prepare baby formula in glass containers, filling feeding bottles after the milk has cooled. The team is now recruiting parents to volunteer samples of their babies' urine and stools for microplastic analysis.

The nano fraction

Particles that are small enough to penetrate and hang around in tissues, or even cells, are the most worrying kind, and warrant more attention in environmental sampling, says Halden. One study[11] that deliberately let pregnant mice inhale extremely tiny particles, for instance, later found the particles in almost every organ in their fetuses. "From a risk perspective, that's where the real concern is, and that's where we need more data."

To enter cells, particles generally need to be smaller than a few hundred nanometres. There was no formal definition of a nanoplastic until 2018, when French researchers proposed the upper size limit of 1 µm — tiny enough to remain dispersed through a water column where organisms can more easily consume them, instead of sinking or floating as larger microplastics do, says Alexandra ter Halle, an analytical chemist at Paul Sabatier University in Toulouse, France.

But researchers know almost nothing about nanoplastics; they are invisible and cannot simply be scooped up. Just measuring them has stumped scientists.

Researchers can use optical microscopes and spectrometers — which distinguish between particles by their differing interactions with light — to measure the length, width and chemical make-up of plastic particles down to a few micrometres. Below that scale, plastic particles become difficult to distinguish from non-plastic particles such as marine sediment or biological cells. "You're looking for the needle in the haystack, but the needle looks like the hay," says Roman Lehner, a nanomaterials scientist at the Sail and Explore Association, a Swiss non-profit research group.

In 2017, ter Halle and her colleagues proved for the first time that nanoplastic exists in an environmental sample: seawater collected from the Atlantic Ocean[12]. She extracted colloidal solids from the water, filtered away any particles larger than 1 µm, burnt what remained, and used a mass spectrometer — which fragments molecules and sorts the fragments by molecular weight — to confirm that plastic polymers had existed in the remnants.

That, however, gave no information on the exact sizes or shapes of the nanoplastics. Ter Halle got some idea by studying the surfaces of two degraded plastic containers she collected during the expedition. The top few hundred micrometres had become crystalline and brittle, she found; she thinks that this may also be true of the nanoplastics that probably broke off from these surfaces[13]. For now, because researchers cannot collect nanoplastics from the environment, those doing laboratory studies grind up their own plastic, expecting to get similar particles.

Using home-made nanoplastics has an advantage: researchers can introduce tags to help track the particles inside test organisms. Lehner and colleagues prepared fluorescent nano-sized plastic particles and placed them under tissue built from human intestinal-lining cells[14]. The cells did absorb the particles, but did not show signs of cytotoxicity.

"You're looking for the needle in the haystack, but the needle looks like the hay."

Finding plastic specks lodged in intact slices of tissue — through a biopsy, for instance — and observing any pathological effects would be the final piece of the puzzle over microplastic risks, Lehner says. This would be "highly desirable", says Halden. But to reach tissues, the particles would have to be very small, so both researchers think it would be very difficult to detect them conclusively.

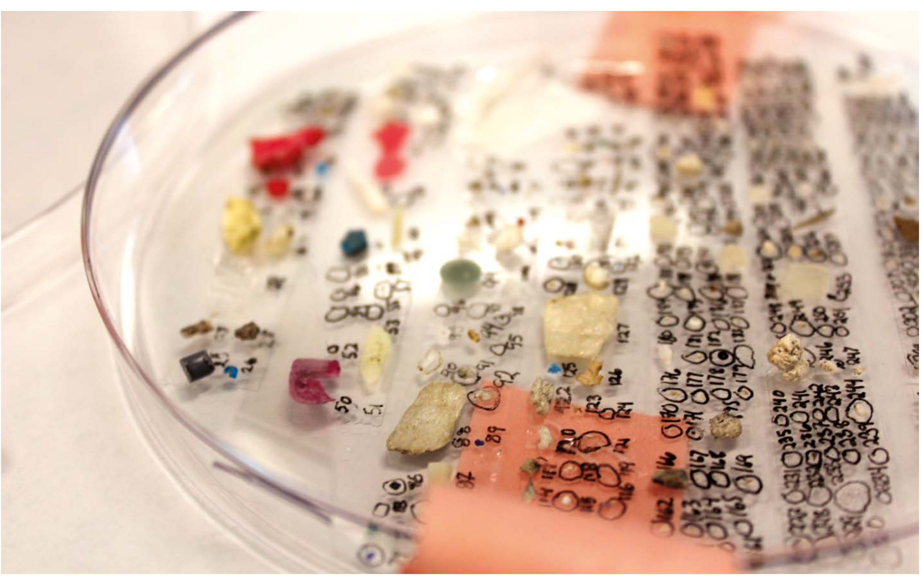
Collecting all these data will take a lot of time. Ter Halle has collaborated with ecologists to quantify microplastic ingestion in the wild. Analysing only particles larger than 700 µm in some 800 samples of insects and fish took thousands of hours, she said. The researchers are now examining the particles in the 25–700 µm range. "This is difficult and tedious, and this is going to take a long time to get the results," she says. To look at the smaller size range, she adds, "the effort is exponential."

No time to lose

For the moment, levels of microplastics and nanoplastics in the environment are too low to affect human health, researchers think. But their numbers will rise. Last September, researchers projected[15] that the amount of plastic added to existing waste each year — whether carefully disposed of in sealed landfills or strewn across land and sea — could more than double from 188 million tonnes in 2016 to 380 million tonnes in 2040. By then, around 10 million tonnes of this could be in the form of microplastics, the scientists estimated — a calculation that didn't include the particles continually being eroded from existing waste.

It is possible to rein in some of our plastic waste, says Winnie Lau at the Pew Charitable Trusts in Washington DC, who is the first author on the study. The researchers found that if every proven solution to curb plastic pollution were adopted in 2020 and scaled up as quickly as possible — including switching to systems of reuse, adopting alternative materials, and recycling plastic — the amount of plastic waste added could drop to 140 million tonnes per year by 2040.

By far the biggest gains would come from cutting out plastics that are used only once and discarded. "There's no point producing things that last for 500 years and then using them for 20 minutes," Galloway says. "It's a completely unsustainable way of being."



COLE BROOKSON

Microplastics collected in the San Francisco Bay area, labelled for study.

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