

An aerial photograph of a beach where the sand is almost entirely replaced by a dense layer of small, colorful plastic fragments, known as microplastics. The debris includes various shades of blue, green, white, and black. A large, semi-transparent blue and yellow geometric shape is overlaid on the left side of the image, serving as a background for the title.

# **MICROPLASTICS: TACKLING THE INVISIBLE ENEMY**

**CAS**



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## Introduction

Plastic pollution is a serious global concern. Although a relatively new phenomenon, the extent of the environmental damage caused by plastics is now well documented. Plastic packaging, such as water bottles, single-use plastic bags, and disposable medical supplies are some of the more recognizable offenders. Removal and recycling of these bigger plastic pieces (macroplastics) has been a growing priority in recent years. Meanwhile, microplastics — small plastic pieces or particles between 1  $\mu\text{m}$  and 5 mm in diameter — have been mostly ignored while they stealthily make their way into our water, food, air, and soil.<sup>1</sup> Scientists have

seen microplastics nearly everywhere they have looked, from falling rain, to arctic snow, to human cells.<sup>2</sup> Their ubiquitous nature has led researchers to investigate the global impact of these tiny specks of plastic.

In this white paper, we analyze the CAS Content Collection™ to provide an overview of the research trends in the growing field of microplastics to understand the general progress of the field, as well as the classes of materials and concepts driving research and innovation.



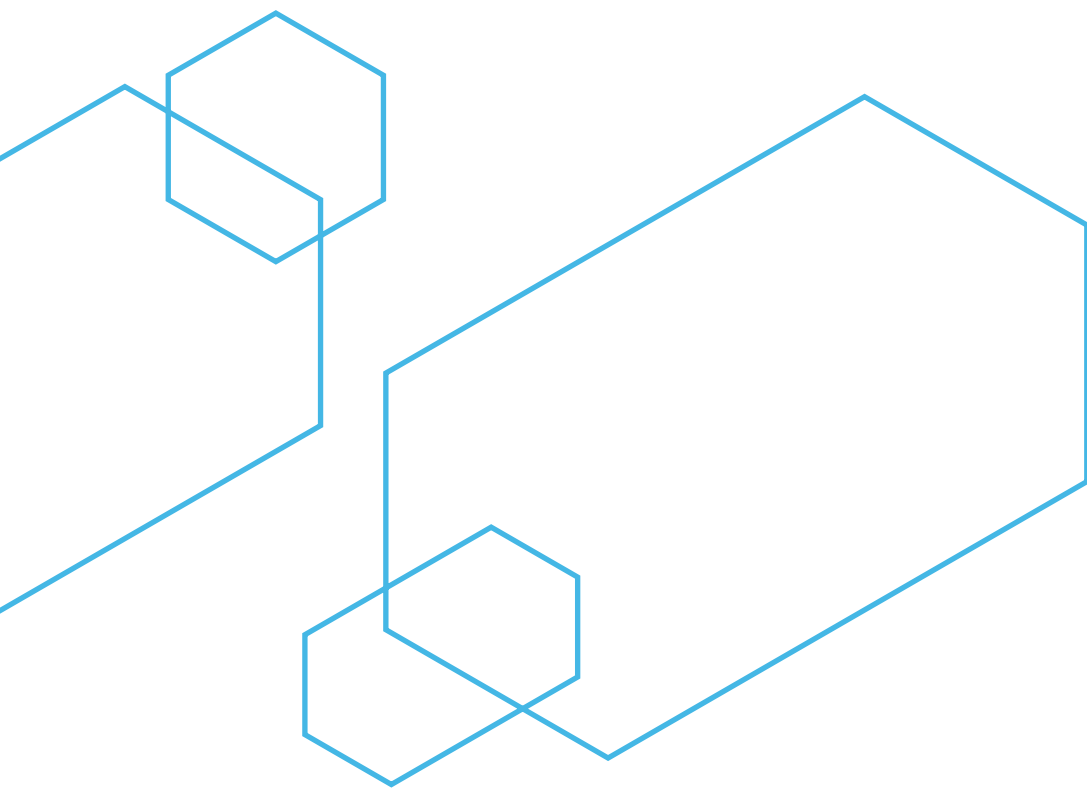
## Microplastics — where do they come from?

To help us understand how microplastics came to be found all over the globe, it's important to consider where they come from. The term 'microplastics' was first coined in 2004 to describe plastic particles smaller than 5 mm in diameter.<sup>2</sup> Microplastics can be broadly divided into two categories: primary microplastics and secondary microplastics.

Primary microplastics are intentionally manufactured as tiny plastic particles measuring 5 mm or less. These can include microbeads in exfoliating hand cleansers and facial scrubs, as well as cleaning agents with abrasive qualities.<sup>3,4</sup> Primary microplastics can also take the form of microfibers: synthetic fibers with a diameter less than 10  $\mu\text{m}$  (approximately 1/100th of the diameter of the human hair).<sup>5</sup> These are typically found in synthetic textiles and are made up of polyester, nylon, or acrylic. They are released from textiles during manufacturing and laundering.<sup>6,7</sup>

Secondary microplastics are formed from the breakdown of larger plastic particles. This breakdown is usually caused by exposure to environmental factors, such as the sun's radiation. Chemical, physical, and biologic exposure can also contribute to the formation of secondary microplastics.<sup>8</sup> Examples include:

- Small debris produced by the abrasion of vehicle tires on road surfaces (natural rubber, styrene-butadiene rubber, polybutadiene rubber, and butyl rubber)<sup>4,9</sup>
- Particles released due to the deterioration of paint, road markings, and marine coatings<sup>10</sup>
- Polyester, acrylic, and polypropylene fibers from textile industry in the form of microfibers<sup>9</sup>



# In air, sea, and soil: the extensive reach of microplastics

With the vast array of microplastic sources, it's easy to see how these pollutants are so prevalent in our environment. Everyday activities, from washing our faces to driving our cars, can contribute to the release of microplastics (**Figure 1**). To understand the reach of microplastics, we have reviewed the key evidence from studies of the sea, soil, and other sources.

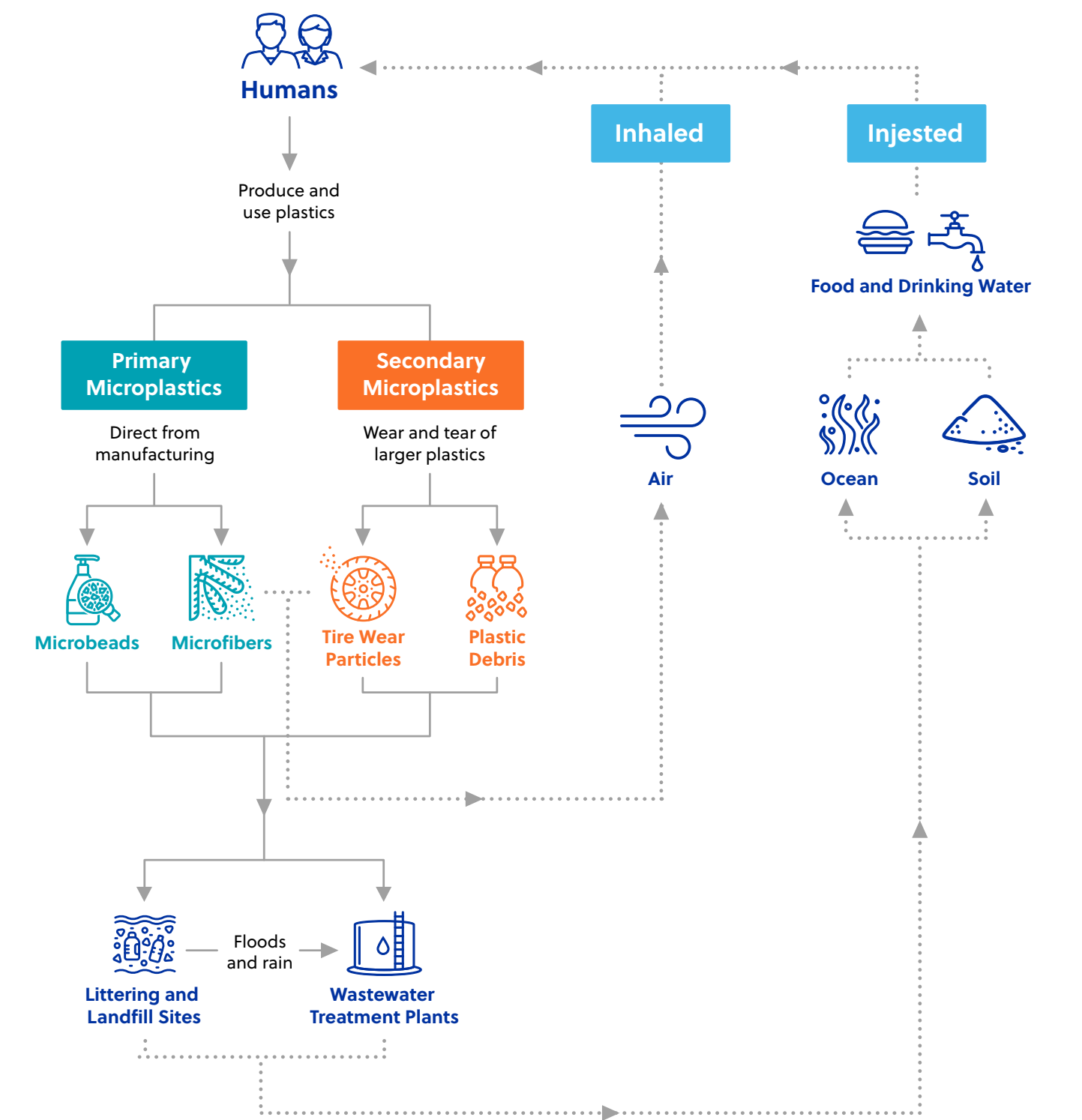


Figure 1. The extensive reach of microplastics



## The sea

The presence of microplastics in water has been widely studied and well-established. In 2010, the oceans were estimated to contain 490,000 tons of plastic.<sup>11</sup> Yet, while larger plastic debris like food containers and bottle caps are typically thought to be the main culprits, microplastics that float in the world's oceans account for a greater amount of plastic pollution.<sup>12</sup> In native sea water, 400 particles of microplastics were found per 1000 L of water, while the microplastic concentration in the North Pacific Subtropical Gyre (a collection of marine debris in the North Pacific Ocean) is approximately 33 per 1000 L of water (or 250 mg microplastics/m<sup>3</sup>).<sup>13,14</sup>

Microplastics, as with most plastic pollution, start out on land. They mainly come from household and commercial waste, entering the ocean from sewer discharges and wastewater treatment plants (WWTPs).<sup>15,16</sup> The smallest microplastic detected in the oceans to date is 1.6 µm in diameter, though the uneven shapes of the particles found suggests that further fragmentation is possible.<sup>15</sup> The majority of oceanic microplastics (69–85%) are secondary in origin, derived from the fragmentation of larger plastic pieces. The remaining 15–31% are estimated to be from primary sources, mainly derived from textile fibers (35%), tire wear particles (28%), and cosmetics (2%).<sup>17</sup>

## Soil and sediments

Though microplastics have been more extensively studied in liquids, solids — particularly soils, sediments, and sewage sludge — are another source of microplastic contamination. Microplastics have been recorded in a diverse range of locations, from a Brazilian beach to an Indian shipbreaking yard and Tasmanian sediments.<sup>14</sup> Furthermore, sewage sludge from North America and Europe is estimated to contribute 700,000 tons of microplastic waste per year, while agricultural films are estimated to add 150,000 tons of plastic per year to Chinese soil.<sup>18</sup>

## The air

Microplastics can be transported in the atmosphere,<sup>19–21</sup> and fall to the ground with snow, rain, or dusty winds. They can also be transported to the Lithosphere/Earth's crust via precipitation and wind. Tiny plastic particles and fibers have been found in remote parts of the French Pyrenees and in snow from the Fram Strait (which lies between Greenland and Svalbard); these have likely been transported from urban areas via the air. Preliminary data suggest atmospheric microplastics may influence cloud formation and could even contribute towards climate change via warming or cooling the atmosphere depending on their location.<sup>22</sup>

## Drinking water

Worryingly, microplastics have made their way into the water we drink. Microplastics of around 960 µm in size<sup>23,24</sup> have been found in tap water at a concentration of around 5500 particles per 1000 L.<sup>11</sup> While there is often a perception that bottled water is cleaner, the presence of smaller microplastics (90% measured at less than 5 µm)<sup>23,24</sup> indicates that drinking water treatment plants are not completely effective in eliminating microplastics.<sup>25</sup>

## Food and the food chain

Microplastics can make their way into the human body through the food chain, and have been recorded in table salt, honey, tea bags, and beer.<sup>26</sup> Overall, 39,000–52,000 microplastic particles were estimated to be consumed per person annually with food, both from the food itself and from particles deposited from the air onto plates and silverware.<sup>27,28</sup> In fact, one study estimated that an average adult is consuming 2000 microplastics per year through the consumption of salt alone.<sup>26</sup>



# The impact of microplastics on human health and natural ecosystems

While the full extent of microplastics pollution has become known, the full impact of this contamination has yet to be revealed. However, research is accumulating regarding the detrimental effects of microplastics on the health of humans and animals. We are continuously inhaling and ingesting microplastics, and the scientific community is working hard to understand the health-related consequences.

## Animals

The effects of microplastics have been studied in a variety of aquatic single-cell and multicellular organisms. Through this research, scientists have observed negative effects ranging from inhibition of photosynthesis to reduced reproduction.<sup>11,13,14,29–38</sup>

Detrimental effects have also been observed in mouse models, with microplastics shown to cause gastrointestinal disturbances from disruptions to the microbiome to impacts on mucus production. Murine studies also indicate that microplastics can contribute to hepatotoxicity, lead to reproduction disorders, and even cause neurotoxic effects.<sup>21,39</sup>

While the mechanisms for these harmful effects are still unclear, evidence suggests that microplastics may be able to transport toxic compounds (e.g., phthalates, unreacted monomers, flame retardants, persistent organic pollutants (POP), pharmaceutical agents, or metals) in a synergistic process thought to further accelerate health-related harm.<sup>30</sup> Evidence suggests that this phenomenon contributes to detrimental biological processes such as gastrointestinal inflammation (mussels),<sup>37</sup> reduced feeding (lugworms),<sup>33</sup> and altered lipid metabolism (European sea bass).<sup>36</sup>

It's important to consider the cumulative effects of microplastic pollution in the food chain. Shellfish and other water-borne organisms act both as sinks for microplastics and present as a source of microplastics for the environment and animals that may eat them. For instance, mussels have been reported to contain 0–4600 particles per kilogram of wet mass, with Chinese mussels containing larger counts of particles than European mussels.<sup>13,40</sup>

## Humans

Humans are constantly inhaling and ingesting microplastics. However, the statistics relating to microplastic consumption vary. For example, one study estimated that each person ingests 14–714 mg of microplastics per day,<sup>41</sup> and a simulation method estimated that as many as 100,000 microplastic particles could be inhaled by individuals annually.<sup>27,42</sup> Microplastics are taken in by organisms via ingestion, inhalation, and skin exposure. Once taken in, the microplastics are transported into cells by membrane translocation or through the placenta or epithelial tissues, through the gaps between epithelial cells, and by endocytosis.<sup>43</sup>

Inhalation and ingestion are not the only ways microplastics can get into our bodies. The use of plastic-containing implants in humans and other mammals has been a known source of microplastic deposition, leading to fibrin deposition and necrosis in nearby joint areas, while macrophages can take up the polymer. In fact, particles were found in the aorta of a dog who had received an implant eighteen months earlier, indicating that sufficiently small microplastic particles can be transported to distant sites in the body.<sup>44</sup>

Microplastics and their associated chemicals and additives are thought to be exerting numerous negative effects on our health, contributing to the development of chronic inflammatory diseases and cancer.<sup>45,46</sup> Chemical additives in microplastics (e.g., plasticizers and flame retardants) can cause harmful biologic effects such as carcinogenicity or endocrine disruption. The presence of ground glass nodules, microfibers, and microplastics has been observed in lung lesions, where it was discovered that the number of microplastics correlated positively with age and the detection of cancer.<sup>45</sup> Additionally, analyses of human feces of people with inflammatory bowel disease (IBD) revealed the presence of smaller microplastic particles (<30 µm) compared with the feces of individuals without IBD. Importantly, the number of fecal particles correlated positively with the severity of IBD.<sup>46</sup>



# The CAS Content Collection: monitoring publication trends in microplastics

The widespread damage caused by microplastics and their impact on the environment and human health is of paramount concern. Using data from the CAS Content Collection, the largest human-curated collection of published scientific knowledge, we explored the research trends in this field via analysis of academic and patent literature from 2011 to 2021. The CAS Content Collection covers publications in more than 50,000 scientific journals from around the world in a wide range of disciplines. Our search formula<sup>a</sup> resulted in a final pool of articles totaling 9,403 (7,789 academic journals and 1,614 patents).

Our analysis revealed that there has been a surge in microplastics research in the last decade. We observed a more than 30-fold increase in microplastic publications in the ten-year period from 2011 (n=81) to 2021 (n=2,811). In contrast, patent publications have not experienced such drastic growth. Although there was almost a three-fold increase in the number of patent publications from 2015 (n=104) to 2020 (n=283), there was a slight reduction in publication numbers in 2021 (**Figure 2**).

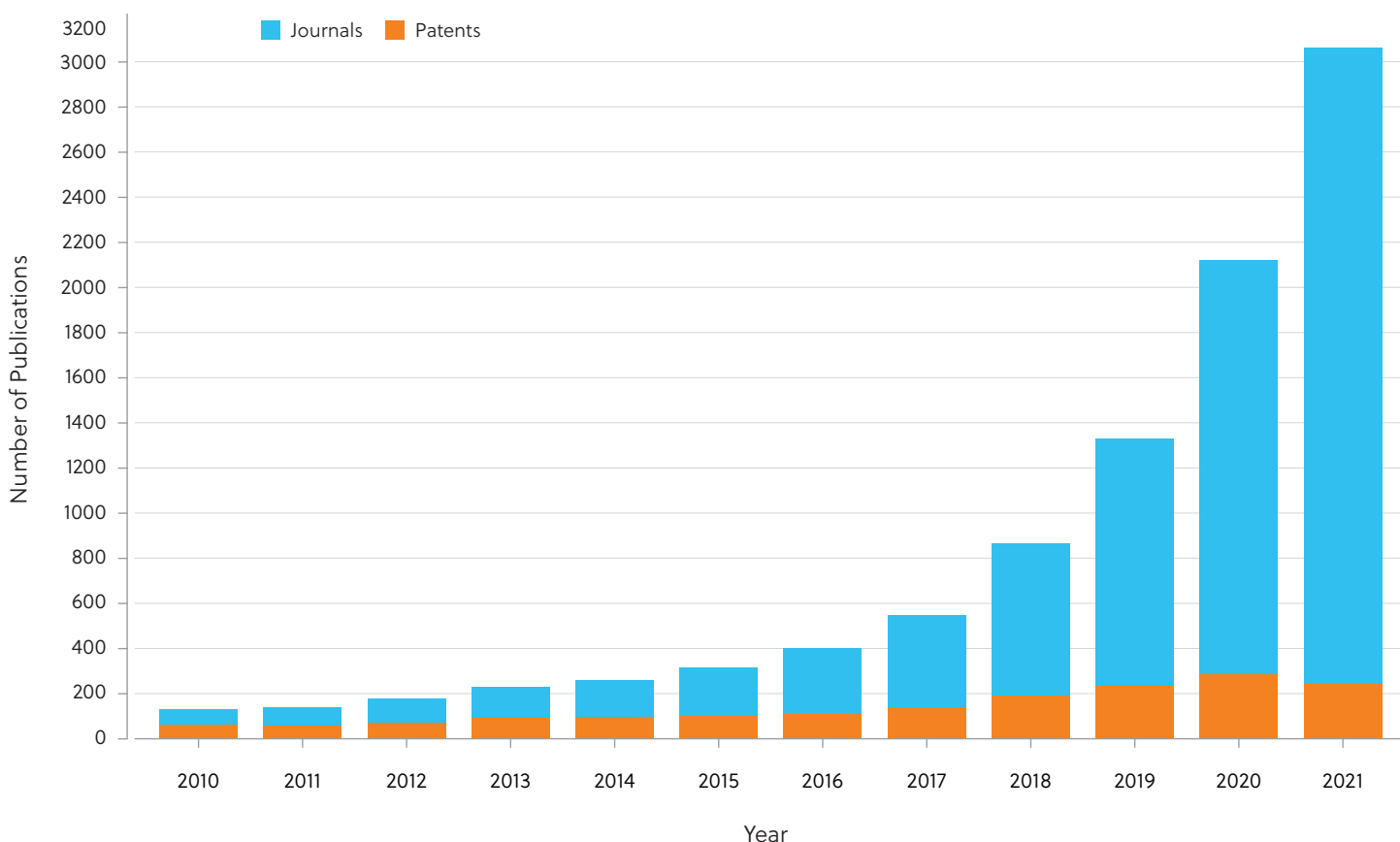


Figure 2. Publication trends of academic journals and patents from 2010 to 2021

<sup>a</sup>Full search query for analysis was (((microfiber? or microplastic? or micro-plastic? or nanoplastic?) and (pollu? or sustainab? or contamin? or health or "synthetic polymeric fiber" or dyes or waste or "synthetic fiber" or "eco-friendly" or toxicity or environment? or ingestion or "fast fashion" or textile or ecosystem or vector or wastewater or soil or remed? or blood or feces or fecal or "human body" or inflamm? or microbi? or recycl? or aquatic or metal or inhal? or indoor or freshwater or circular or seawater or marine or bioaccumul?)) not (fragrance or inhibitor or sensor or cof or "covalent organic framework" or spinning or electrospinning or surgery) and 2010-2022/py).

We further examined the distribution of publications by country (**Figure 3**). China is leading the way in publishing microplastic data, followed by the US, Germany, South Korea, and Italy. Between 2011 and 2021, China published both the highest number of journal (n=2,291) and patent (n=715) publications, and was found to be the originator of 10 out of 15 patent assignees associated with publications. Other top-ranking organizations in terms of journal articles and patents include those from the US (Biomass

Energy Enhancements LLC and North Carolina State University), UK (GE Healthcare UK Limited), and Germany (Carl Freudenberg KG).

Generally, we observed that academic institutions remain dominant in patent publications, with smaller contributions from the private industry. This may be due to the lack of economic incentives associated with resolving the issue of microplastics.

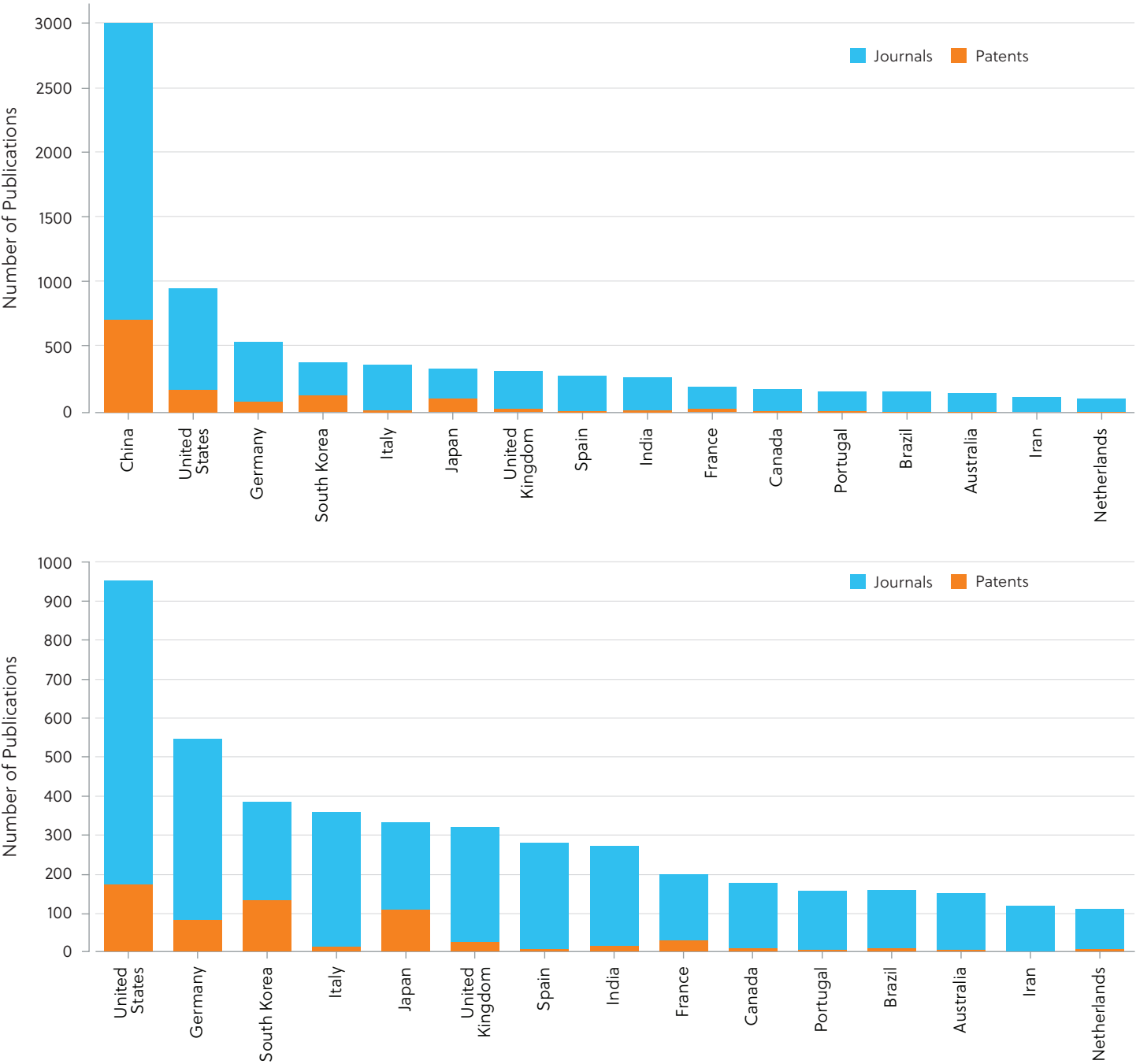


Figure 3. Journal and patent publications on microplastics by top organization countries/regions both including China (A) and excluding China (B)





Using data from the CAS Content Collection, we examined the substances most mentioned in microplastics publications (Figure 4). These results revealed that the number of journal articles far exceeded the number of patent publications for each registered substance. The top five substances were shown to be ethene homopolymer (polyethylene), polystyrene, 1-propene homopolymer (polypropylene), polyethylene terephthalate (PET), and polyvinyl chloride (PVC). These five substances happen to be the same polymers most commonly found in environmental microplastics.<sup>47–49</sup>

The sixth mentioned substance was cellulose, which is considered a microplastic in some studies.<sup>50–52</sup> However, its presence on the list may reflect attempts to use this substance as a replacement for synthetic polymers in applications such as electronics, textiles and in sustainable biomaterials. Cellulose has also been studied for its potential ability to remove microplastics from the environment.<sup>53–58</sup>

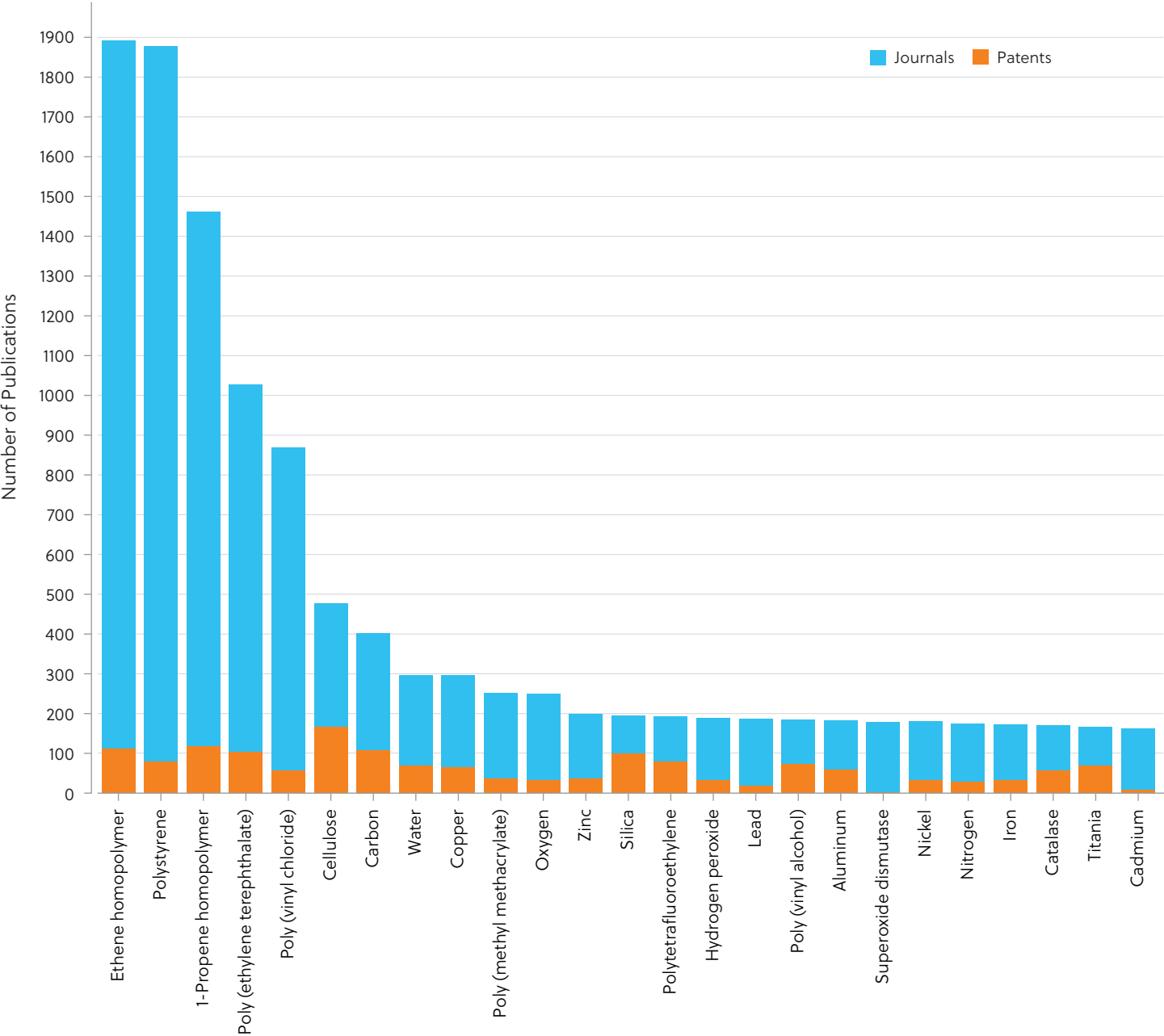


Figure 4. Top registered substances in microplastic publications

Analysis of the substance class distribution of the total of substances recorded per year reveals several research trends (**Figure 5**). There has been a notable rise in the recorded number of polymers, reflecting an increase in interest in studying microplastics as a phenomenon. However, the substance class that has seen the largest increase in research interest is 'organic/inorganic small molecules' from 2017 onwards. This is potentially due to several factors, including the identification and measurement of small molecules and monomers released as plastic degradation occurs, the transfer of pollutants from the environment into living organisms via microplastics, and the study of individual chemical additives to plastics that can seep from microplastics.<sup>59–64</sup>

Another substance class that has seen a rise in research activity is the 'element' class, with the number of publications increasing significantly in 2020 and 2021. This is likely to be due to the growing interest in carbon (specifically activated carbon) for water treatment and purification, including the removal of microplastics.<sup>65</sup> Carbon is also mentioned across several diverse microplastics publications due to the impact of microplastics on processes involving this essential element, such as the carbon cycle.<sup>66–70</sup> Other elements featuring in microplastics research include As, Cd, Cr, Cu, Pb, Mn, and Zn. This is potentially due to the identification of microplastics as vectors for these particular elements.<sup>71,72</sup>

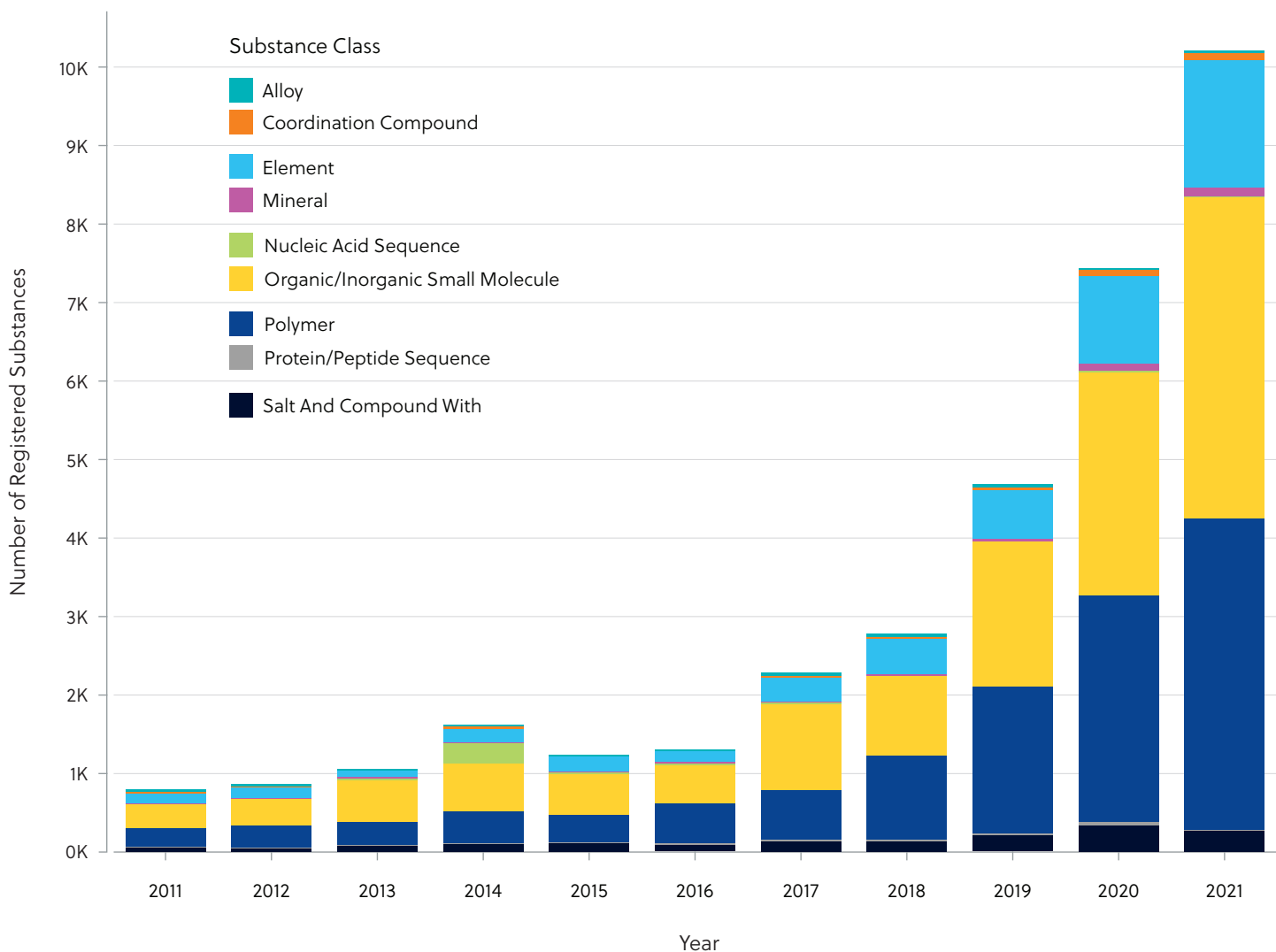
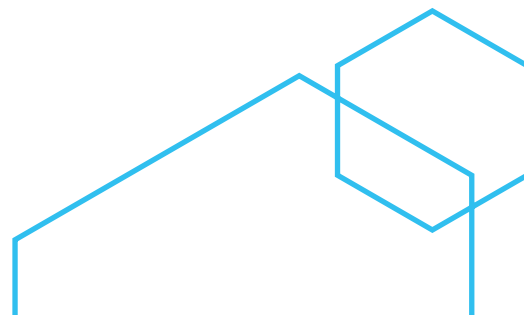


Figure 5. Substance class distribution of total registered substances per year from 2011–2021 in microplastics research



## Measuring the impact of microplastics

Analysis of the CAS Content Collection indicates that microplastics research is growing. While the analysis paints a picture of the type of research being conducted, the true impact of microplastics is more challenging to measure.

We know that microplastics are everywhere, from the water we drink to the air that we breathe. However, following ingestion, it is difficult to quantify the proportion of microplastics that are excreted compared with those that are retained in biological systems. We know that microplastics can be excreted in a variety of ways: by transfer to bile, urine, exhalation, cerebrospinal fluid, and even breast milk.<sup>44</sup>

Though the uptake of microplastics has not been fully elucidated, the shape and surface functionalization of microplastic particles are likely to have an impact on their uptake, biological activity within the body, and their toxicities. We know that smaller particles are more readily taken up compared with larger particles. Shape is another key factor that impacts on levels of retention, with particles thought to be more readily retained than fibers.<sup>44,73</sup> Therefore, refinement of analytical tools to detect and quantify smaller microplastic particles (nanoplastics) is essential for us to confirm exposures and effects.

## Eliminating microplastics from the environment

A key research priority in microplastics research is remediation — removing existing microplastics from the environment. But is this an achievable goal? Several methods have been proposed specifically for microplastic removal from water, including:

- Adding microplastic-capturing filters to cargo ships, allowing microplastic particles to be collected while ships are in motion<sup>74</sup>
- Using the ship's ballast system to filter microplastics from water before it is discharged back to the sea<sup>75–77</sup>
- Use of plastic waste collecting systems called 'interceptors', which can float on the surface of oceans and rivers and collect plastic debris. While these systems are not designed specifically for microplastics, they are thought to be effective in capturing particles of a certain size (smaller than 0.5 cm)<sup>78</sup>
- The use of mussels, where, following ingestion of microplastics, their fecal waste floats on the water's surface in the form of pellets, which can be collected easily<sup>79</sup>

Despite these techniques yielding some promising results, the sheer volume of ocean water means that removing microplastics directly from it would require large amounts of time and effort. Furthermore, related research in the area is sparse. A more feasible approach may be to focus on stopping microplastics entering the environment in the first place. Examples of such methods mentioned in the literature include:

- Wastewater treatment plants that are proven to be effective at microplastic removal, especially at the tertiary level (e.g., dissolved air flotation, rapid sand filtration, membrane bioreactors). However, complete system removal may be unlikely; for example, microplastics diverted into sewage will end up in the water supply again<sup>80–82</sup>
- Laundry accessories to prevent the release of microfibers from synthetic textiles into wastewater systems<sup>83</sup>
- Reassessment of clothes manufacturing processes to minimize friction, improve the mechanical integrity of garments, and use biodegradable, rather than plastic materials<sup>84,85</sup>



**Figure 6** shows the number of publications involving various keywords related to microplastics removal. The number of publications for most keywords grew sharply since the mid-2010s, suggesting a growing awareness of the microplastics issue. Consequently, we have also seen an increase in publications related to microplastic removal. Yet, it's important to be mindful of nuances that could skew our interpretation of the data. For instance, some terms such as "filtration" and "WWTP" could

be misleading as there is overlap with other studies that do not specifically relate to microplastic removal. However, the trends do give us an indication of the level of research interest in different methods being explored. Membrane bioreactors were featured in several studies, suggesting the popularity of this newer, highly efficient removal method. In contrast, document counts for "coagulation", "flotation", and "flocculation" are low, reflecting less interest in these basic removal techniques.

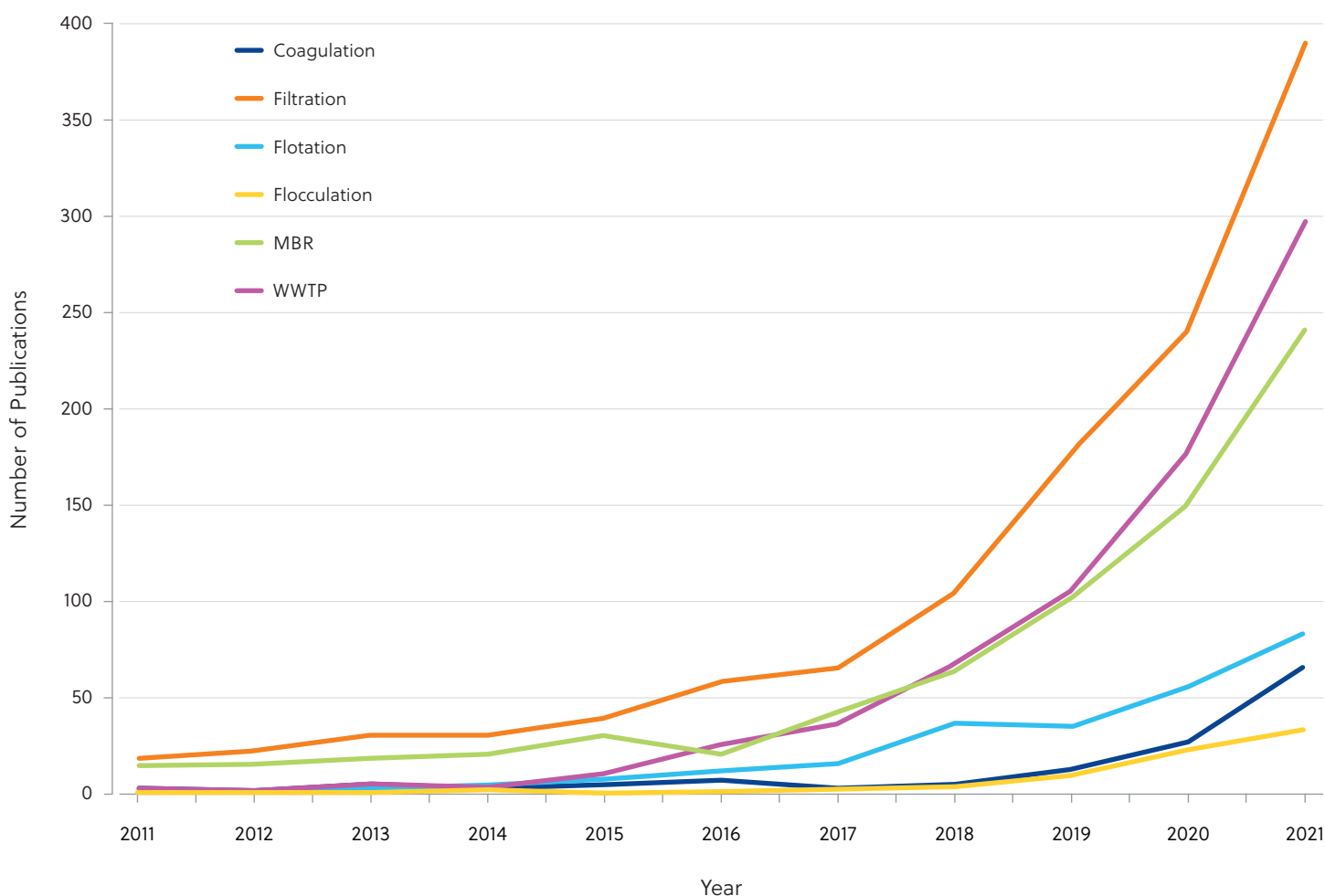


Figure 6. Publication volume related to some microplastics removal techniques (MBR, membrane bioreactor; WWTP, wastewater treatment plant)



## Regulating microplastic production and use

In the past few years, we've seen official regulations around plastic use passed in several countries including the U.S., China, Canada, and parts of the EU. A notable milestone is the banning or restriction of cosmetics and drugs containing plastic microbeads.<sup>86–88</sup> However, microbeads account for only 2% of primary microplastics, which themselves comprise only about 20–30% of all microplastics.<sup>83</sup> Although synthetic microfibers make up 35% of primary microplastics, regulations concerning these have been non-existent, with the exception of a law in France requiring microfiber filters to be installed in new washing machines by 2025.<sup>89</sup>

Regulating the manufacturing, use, and recycling of plastic products is a critical aspect of secondary microplastic control, as these appear in the environment over time following plastic degradation. Single-use plastics, such as straws, plates, and polystyrene cups/containers are now banned in many countries,<sup>90</sup> while plastic bag levies are commonplace.<sup>91,92</sup> It is hoped that regulations such as these will help address the issue of secondary microplastics.

## Conclusions

Microplastics are a growing global concern, with particles being found in water, salt, foods, soil, and even in the air. Emerging evidence suggests that these microscopic particles and their associated chemicals are detrimental to the health of animals and humans. However, the exact cause and magnitude of harm is not yet clear.

As an expert-curated resource, the CAS Content Collection was employed to perform quantitative analysis of microplastic-related publications over

time, across countries/regions, specific research areas, and substances. The analysis indicated a worrying lack of innovation in microplastics research, with patents comprising only a small proportion of the total publications. Furthermore, academic institutions dominate both journal and patent publications, indicating a general lack of industry investment. Yet, we need a concerted effort among scientists, entrepreneurs, governments, and the public to combat microplastic pollution.

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