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Perspective

Microplastics in the Great Lakes: Environmental, Health, and Socioeconomic Implications and Future Directions

Claire Fuschi, Haihui Pu, Margaret MacDonell, Kurt Picel, Maria Negri, and Junhong Chen*

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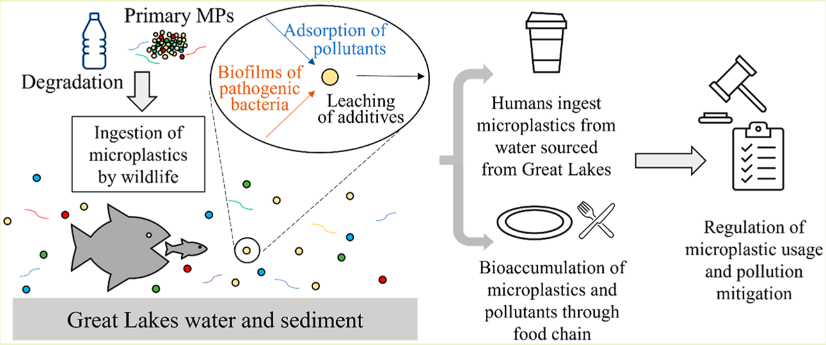

ABSTRACT: Microplastics (MPs) are tiny pieces of plastic (<5 mm) that have been manufactured, shed from textiles, or formed as the degradation products of macroplastics. They can be taken up by aquatic organisms, leading to their incorporation into the food chain. Humans can consume MPs from fish as well as other impacted sources including bottled and tap water. MPs may pose risks to exposed organisms, and they can also act as vectors carrying additional adsorbed chemical pollutants and pathogens. MPs are an especially important focus regarding the Great Lakes because plastics comprise most of the litter, and the Great Lakes serve as a source of drinking water for 40 million people. This perspective summarizes the current state of MP pollution in the Great Lakes and potential risks posed to the environment, wildlife, and humans. A survey of detection, separation, and quantification methods is included. Potential remedies are explored, focusing on policy, human behavior, and the goal of a circular economy. Further research directions include standardizing detection and removal methods, assessing the health risk of MPs in the Great Lakes, and evaluating mitigation options.

KEYWORDS: *Microplastics, Pollution, Great Lakes, Hazards, Regulation*

INTRODUCTION

Microplastics (MPs) are pieces of plastic less than 5 mm in length,[1] and they exist in a variety of shapes, sizes, colors, polymer types, and densities. MPs can originate from multiple sources, and they are reported to have been found in 90% of surface waters worldwide.[2] Primary MPs are manufactured for commercial and industrial uses, such as glitter[3] and nurdles (which are pellets used to make plastic products).[4] These materials are not readily biodegradable, so when MPs enter the environment, they tend to persist. Until a few years ago, a number of exfoliant cleansers contained microbeads smaller than 2 mm in diameter at levels up to 10% by weight.[5] Most microbeads in personal care products are 1 mm or smaller. Although the United States banned these beads from rinse-off cosmetics and over-the-counter drugs such as toothpaste in 2015 (the ban went into effect in 2018), many years of discharges prior to the ban and releases from other products have resulted in their presence in U.S. surface waters, including the Great Lakes.

Primary MPs can also be generated by washing clothes made of polymer fabrics such as polyester, nylon, and acrylic,[3] just as microfibers can be generated by washing natural fabrics such as cotton and wool. Various estimates of MPs in surface waters across the globe suggest that microfibers from multiple sources might account for roughly 70% to 90% of the total.[2] Ross et al. analyzed MPs in the Arctic Ocean and found that 73% of synthetic fibers present in the collected samples were polyester microfibers and resembled characteristics of polyethylene terephthalate (PET) from textiles, suggesting that much of the ocean's MPs could originate from home laundry.[6] Vassilenko et al. reported that a single clothing item could release more than a

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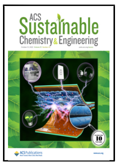

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hundred to seven hundred thousand fibers during a laundry cycle, with a wide range of values affected by conditions ranging from the ratio of water to textile to temperature, use of detergent, first laundering, and more.[7,8] The same study estimates that the annual release of microfibers to the aquatic environment from all households in Canada and the United States combined could total 878 t, with U.S. households accounting for more than 90% (per more than 127 million households compared with 14 million for Canada, based on 2018 and 2017 census data, respectively).[6] Interestingly, the reported average number of natural microfibers released from laundering cotton and wool textiles was essentially the same as the highest average among all synthetic textiles reported (which was for mechanically treated polyester fleeces and jerseys, about 6-fold higher than that for woven nylon textiles with filament-type yarn).

Secondary MPs originate from fragmentation of larger plastics like water bottles and plastic bags due to environmental degradation processes that include biodegradation, photodegradation, oxidative degradation, thermal degradation, and hydrolysis.[9,10] Because of the vast amount of macroplastics that enter the environment, many have assumed that most MPs are secondary MPs.[11,12] Globally, the most commonly produced polymers are polyethylene (PE), including high- and low-density (HDPE and LDPE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), including expanded polystyrene (EPS), and PET.[13,14] These polymers are also commonly found in freshwater systems. Among their many uses, PVC, PS, and PET are used to make food and beverage containers and packaging; HDPE and LDPE are used to make plastic bags, bottles, and other containers; and PP is used to make bottles and other containers as well as toys.[15−17] Thus, many of the MPs contaminating the Great Lakes are likely the result of macroplastic degradation.

Wastewater treatment plants (WWTPs) are a source of MPs in aquatic environments.[18] From a recent review of 21 studies, Iyare et al. reported that, on average, preliminary and primary treatment WWTPs remove 72% of MPs from influent wastewaters, while plants with secondary treatment remove 88% and those with tertiary treatment remove 94%.[19] In 2014, Arvai et al. reported that nearly 1,450 municipal WWTPs collectively discharged 4.8 billion gallons of treated effluent daily to the Great Lakes basin, and treatment plants with secondary and higher treatment accounted for 98% of the total wastewater flow discharged to the basin. The authors also noted that secondary treatment is a minimum standard for U.S. WWTPs, and analyses of treatment performance with respect to total wastewater flow showed that more than 95% of the wastewater discharged into the Great Lakes basin met the performance requirement for advanced treatment.[20] Thus, most WWTPs discharging to this basin are capturing most of the MPs they receive, consistent with the general finding that 90% or more of MPs in influent wastewaters are removed to the sludge of a WWTP.

Despite the small fraction released with effluent, individual particle and fiber counts can be substantial and accumulation is ongoing. A study by Conley et al. of three WWTPs in South Carolina reported MP removal efficiencies ranging from about 85% to more than 97%. Using source modeling, they estimated that for smaller plants with lower removal efficiencies, up to 600 million MP particles might be released daily.[21] For an annual perspective, Freeman et al. estimated that even a removal efficiency of 99% for particles with any dimension less than 100 μm could lead to upward of 100 billion MP particles released from a WWTP over a year.[22] Because most influent MPs are removed to the WWTP sludge, the land application of these biosolids (most often to amend soil on agricultural lands) can be a source of MPs in aquatic systems via surface runoff. Meanwhile, WWTP sludges that are disposed of in landfills also represent a source of MPs in the terrestrial environment. Sewage overflow events[21] and stormwater runoff[23] are other sources of MPs in aquatic environments. As an example of the latter, Werbowski et al. found that stormwater runoff in the San Francisco Bay contained many more MP particles than wastewater effluent, with fibers and black rubber fragments, likely originating from road-worn tires, comprising about 85% of all particles in the runoff.[23]

MPs are also found in drinking water, from both bottled and tap water samples. In a study of 159 samples from 14 countries, Kosuth et al. found that 81% contained anthropogenic particles, a general term indicating MPs.[24] From the more than 30 samples across 19 U.S. cities, the mean concentration was about 9 particles/L. In a study of three drinking water treatment plants in the Czech Republic, Pivokonsky et al. found that MP removal efficiencies ranged from 70%−83%. For MP fibers, the treatment plant that used only basic coagulation, flocculation, and sand filtration achieved a removal efficiency of 25%, while the two plants that included a conventional activated carbon finishing step achieved 80% to 90% removal.[25] Like for wastewater treatment, the authors found that, in general, traditional drinking water treatment processes are promising for removing MPs and suggested optimizing conditions (such as coagulant dose, pH, and residence time) as well as evaluating more advanced treatment technologies to increase removal efficiencies.[26]

Because MPs are so common and persistent in the environment, questions arise regarding potential ecological and human health effects as well as potential remedies and mitigations. The Great Lakes are a source of drinking water for 40 million people, 10% of the United States population and 30% of the Canadian population. The Great Lakes account for 84% of North America's surface fresh water and 21% of all surface fresh water in the world, and their maritime economy supports more than 300,000 jobs, translating to $8.8 billion in wages.[27] Considering just one aspect of this economy, the Great Lakes commercial, recreational, and tribal fisheries are valued at over $7 billion annually and support over 75,000 jobs.[28] Thus, MP contamination in the Great Lakes has the potential for substantial impacts, and the need to better understand, control, and reduce this contamination is increasingly urgent.

CURRENT STATE OF MICROPLASTIC POLLUTION IN THE GREAT LAKES

The Great Lakes span more than 94,000 square miles and account for 95% of surface freshwater in the United States and 18% of the world's surface freshwater supply. Given this scale, our understanding of MP pollution across the Great Lakes is very limited. As public awareness of MPs in the environment has increased, so too have research studies, and more information continues to be developed that helps frame the issues. According to calculations by the Rochester Institute of Technology, nearly 22 million pounds of plastic debris enter the Great Lakes every year, with most (11.6 million pounds) entering Lake Michigan. Following that are Lake Erie (5.6 million pounds), Lake Ontario (3.2 million pounds), Lake Huron (1.4 million pounds), and Lake Superior (more than 70,000 pounds).[29] Further, most shoreline litter is plastic. For example, of more than 25,000

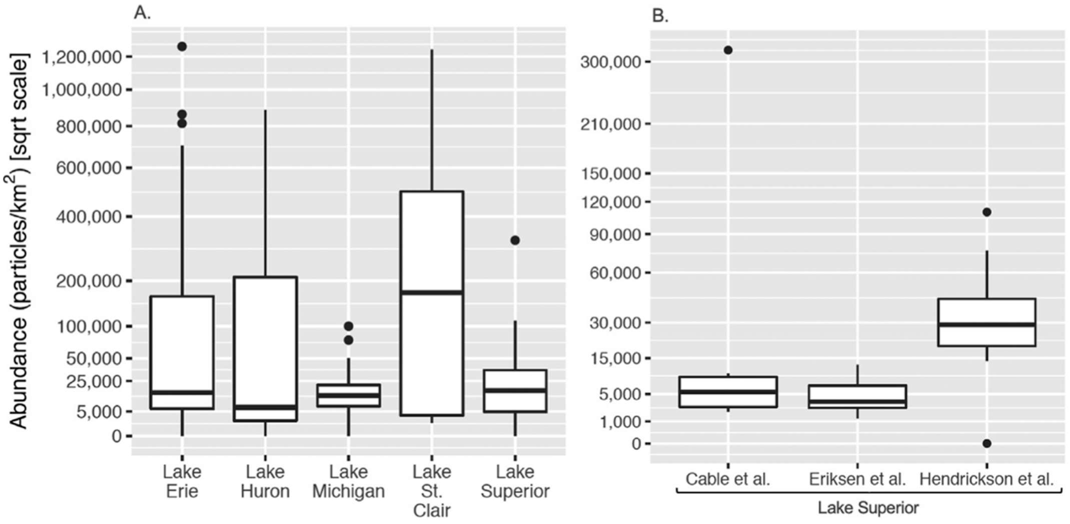


Figure 1. (A) Reported concentrations of MPs within the surface waters of five lakes in the Great Lakes system. (B) Three studies report MPs concentrations within Lake Superior. Note change of scale on *Y*-axis between (A) and (B). Reprinted with permission from ref 34. Copyright 2021 Elsevier.

pounds of trash volunteers removed from Great Lakes beaches in 2021, more than 85% was at least partly plastic.[30] Debris that collects on shorelines likely fragments into smaller pieces over time, adding to existing MPs in the lake system.

The distribution of polymers in the lake system varies, as illustrated by a study from Lenaker et al. of 20 sediment samples from Lake Michigan and 12 from Lake Erie.[31] They reported that PET, HDPE, and semisynthetic cellulose (S.S. Cellulose) were most common among the 37 particles analyzed from Lake Michigan sediment; and synthetic cellulose, PP, and PVC were most common among the 44 particles analyzed from Lake Erie sediment. The authors also synthesized results of other Great Lakes studies that reported low-density MPs such as EPS foams and PP fragments were more abundant in surface water samples while higher-density particles such as PET were more abundant lower in the water column and into the sediment. Also, fibers were much more prevalent in surface samples from the tributaries than in the Great Lakes. Those results suggested denser particles are likely settling out in the Great Lakes, which could help explain the difference in relative abundance of fibers in tributary versus lake surface water samples. These findings are consistent with the those of Koelmans et al. from their review of multiple studies that focused on MPS in freshwater—notably that the relative abundance of polymer types likely reflects plastic production and polymer density differences.[10]

McNeish et al. sampled fish from three Lake Michigan tributaries and analyzed them for the presence of MPs. They found that 85% of the fish (across 11 different taxa) contained MPs in their digestive tracts, with an average of 13 particles per fish.[32] MPs have also been found in the guts of fish from Lake Ontario and Lake Superior, making up 35% to 59% of the total anthropogenic particles found in the fish, and surpassing levels of MPs found in marine organisms.[33] Kosuth et al. investigated the level of MPs in 12 brands of beer made with water sourced from the Great Lakes, as well as tap water from seven of the nine municipalities represented within the brands. The average concentration found in beer was about 4 particles/L, and the average in tap water sourced from the Great Lakes was about 1.6 particles/L.[24] These studies and others indicate the extent to which MPs permeate the Great Lakes ecosystems.

Earn et al. published an in-depth review in which they collected data from 11 papers to summarize the current state of knowledge regarding MP concentrations in the Great Lakes.[34] They reported high variation among studies, likely based on sample locations and sampling and analysis methods. Overall, reported surface water concentrations ranged from 0 to about 318,000 particles/km^2 in Lake Superior,[34−37] 886,000 particles/km^2 in Lake Huron,[34−36] 100,000 particles/km^2 in Lake Michigan,[38] and 1,264,000 particles/km^2 in Lake Erie,[34−36] with a similar upper value (nearly 1,244,000 particles/km^2) reported for Lake St. Clair (note that this relatively small lake has roughly 1% the volume of Lake Ontario and is not typically included in the set of Great Lakes)[34] (Figure 1A). Earn et al. ranked the lakes from highest to lowest by average MP concentrations in round numbers, as follows: Lake St. Clair (355,000 particles/km^2), Lake Erie (162,000 particles/km^2), Lake Huron (111,000 particles/km^2), Lake Superior (35,000 particles/km^2), and Lake Michigan (17,000 particles/km^2). Cox et al. published a study quantifying the concentration of MPs in Lake Superior surface water after Earn et al. published their review, reporting about 30,000 particles/km^2 on average,[39] which is very similar to the average reported by Earn et al. As noted, these estimates are from a relative handful of measurements considering the vast expanse of the Great Lakes, and reported concentrations range over multiple orders of magnitude. Earn et al. illustrated the high variability across the limited set of samples for a single lake, as shown in Figure 1B.[34]

The average MP concentrations presented in studies of the Great Lakes are comparable to those from marine surveys in the South Pacific Gyre, the North Atlantic Gyre, and the North Pacific Gyre—which have been reported as 26,900 particles/km^2, 20,300 particles/km^2 and 334,300 particles/km^2,[10,40,41] respectively, suggesting that the Great Lakes are similarly polluted with plastics as those impacted marine settings. Interestingly, the Great Lakes may be more at risk to MP creation than oceanic gyres according to Driedger et al.[42] This is because the surface currents in the Great Lakes are not steady like in oceanic gyres and instead are impacted by short bursts of surface wind stress. The Great Lakes also have a greater shoreline-to-surface area ratio, and these two factors combined would intensify debris interactions with the shoreline where plastic debris is subject to more intense mechanical and photooxidative degradation.[43] In fact, macroplastic debris from the Great Lakes has already been confirmed to be undergoing mechanical and oxidative weathering, suggesting they are degrading into MPs. Of samples from Lakes Huron, St. Clair, and Erie combined, 78% and 37% showed signs of mechanical and oxidative degradation, respectively.[44] The hydraulic residence time of water in the Great Lakes may also play a role in the amount of MPs that persist in each lake. For example, Hoffman and Hittinger[29,45] modeled MP movement throughout the Great Lakes and found that Lake Michigan and Lake Superior had the lowest number of particles leaving to other lakes. They hypothesized this was due to the longer hydraulic residence times of Lake Superior (173 years) and Lake Michigan (62 years) compared to Lake Huron (21 years), Lake Ontario (7.5 years), and Lake Erie (2.7 years).[29,45] More research is warranted to explore the sources and fate of MPs across the Great Lakes, to understand potential exposures.

POTENTIAL HAZARDS

MPs and nanoplastics (NPs) have been shown to contaminate every level of the food web in the Great Lakes—spanning algae,[46] invertebrates, mussels[47] and fish,[32,33] and they have been shown to bioaccumulate in both freshwater and marine species.[48,49] In addition to the hazards posed by these MPs, chemicals added during plastics production such as plasticizers and flame retardants can leach out as they degrade in the environment. Moreover, MPs can carry sorbed pollutants and bacteria in biofilm that establishes on their surfaces. Given the scale of the Great Lakes, relatively few data are available to quantitatively assess hazards and risks associated with its MPs. More information is needed about the suite of compositions, characteristics, environmental fate and transport aspects, and concentrations of MPs at numerous exposure points over the wide range of environmental conditions in space and time that represent the Great Lakes system. With regard to ecological hazards, in a quality criteria assessment of MP effect studies, deRuijter et al. found that the weight of evidence was strongest for mechanisms related to inhibition of food assimilation and/or decreased nutritional value and those related to internal and external physical damage.[50] Food dilution can occur when organisms ingest low-calorie MPs, supplementing some of their normal food intake. Koelmans et al. examined nine studies that quantified the hazardous concentrations for (the most sensitive) 5% of the species in an aquatic community (HC_5) and found that reported values ranged from less than 1 to about 100,000 particles/L, with a median of nearly 76 particles/L.[12]

Laboratory experiments can shed light on what potential effects may occur from MP exposure, recognizing that relevance to environmental exposure conditions is crucial if results are to be useful for risk assessments. The rodent model has been used for decades to assess potential human toxicity. In a 90-day rat study (representing subchronic exposure), ingestion of water containing 5 mg/Land 50 mg/L of PS MPs induced cardiomyocyte apoptosis and oxidative stress, with implications for subsequent heart fibrosis and cardiac dysfunction.[51] In a mouse study, ingestion of water containing PS MPs at 0.1 and 1 mg/L induced gut damage and metabolic disorders at the higher dose.[52] For ecotoxicity, medaka are a common test organism. Exposure of this fish to a nominal concentration of 100,000 PS MP particles/L for 48 h led to inhibition of growth and egg production.[53] In a related species, exposures of larval zebrafish to PS MPs 5 and 50 μm in diameter at concentrations of 0.1 and 1 mg/L for 7 days induced microbiome dysbiosis and changes in metabolomic profiles.[54] In another 48 h aquatic toxicity test with a different MP, exposure of the freshwater crustacean *Daphnia magna* to ground (milled) PET textile microfibers led to increased mortality at concentrations of 12.5 to 100 mg/L (variability was high).[55] Meanwhile, in a terrestrial invertebrate toxicity study, earthworms exposed to PS MPs at concentrations of 1−2% g/g soil for 30 days exhibited decreased growth and increased mortality.[56]

Earn et al. completed a review of 75 studies that investigated the impacts of plastic debris on freshwater biota. 99% were laboratory studies (where concentrations are 10 orders of magnitude higher than in the environment), and nearly all tested MPs, measuring effects such as mechanical stress or changes in reproduction, behavior, growth, and development.[34] They found that of nearly 400 effects tested across the studies, 60% were detected—and about two-thirds of these were at ecologically relevant levels that spanned organism, population, community, and ecosystem. From their analysis of 20 studies, Earn et al. determined that the likelihood of an effect being detected is influenced by the type, size, and shape of MP tested. Regarding shape, they noted that although microfibers caused an effect in 58% of cases, all those data points were from the same study. Based on data from 5 studies, they found that spheres were reported to cause an effect in 45% of cases, while data from 19 studies indicated that fragments caused an effect in 24% of cases. The authors acknowledged that others had reported fibers and fragments tended to be more harmful than spheres. Regarding size, like others, Earn et al. concluded that the smaller the MP, the more likely it is an effect will be detected. This pattern was especially seen in spheres, with the smallest particles (0.01 to 0.09 μm) causing an effect in 88% of instances while only 43% and 27% of effects were detected in the next larger size classes (1−9 and 10−90 μm, respectively). An increasing number and severity of effects for smaller particles is a trend that has been shown in literature,[57−59] likely due to the ability of smaller micro- and nanosized particles to cross the intestinal barrier and translocate to other systems and tissues.[60,61]

Furthermore, the surfaces of MP particles can serve as a substrate for biofilm growth, which can lead to the sorption of other pollutants, including the (hydrophobic) per- and polyfluoroalkyl substances (PFAS).[62] Researchers from the Illinois Sustainable Technology Center submerged samples of three common types of MPs in Muskegon Lake water and in the channel connecting it to Lake Michigan for one and three months, and in the laboratory water for one month. They found that PFAS consistently adhered to all types of MP particles, and that the MPs adsorbed more PFAS from lake or channel water than from laboratory water, 24 to 259 times compared to 1/7 to 1/4 times the background levels. PFAS amount adsorbed ranged from 0.052 nanogram to 0.87 nanogram PFAS per gram of plastic in the Muskegon Lake water. This is likely due to the organic matter in the lake water that formed biofilms on the MPs and aided adsorption.[62] Two heavily studied PFAS, perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS), can cause cancer, reproductive and developmental issues, liver and kidney damage, and immunological effects in laboratory animals.[63] Vosshage et al. found that snails (R. balthica) that grazed on biofilms grown on plastic substrates exhibited reduced growth rates compared to the control which fed on biofilms grown on glass.[64]

Moreover, biofilms are not only composed of the same microbes found in the surrounding water environment but include bacteria that are distinct, and sometimes more pathogenic than the surrounding environment. Wu et al. found that compared to biofilms on rocks and leaves, biofilms on MPs "selectively enriched" certain antibiotic-resistant genes (ARGs) and other pathogenic bacteria.[65] McCormick et al. found that MPs collected from nine Illinois rivers had microbiomes that were less diverse than the corresponding natural substrates, and contained greater populations of common human intestinal pathogens.[66] Biofilm formation ends with the formation of top-level communities or the diffusion of biofilms into the water matrix,[67] which suggests that biofilms on MPs could serve as vectors of pathogenic bacteria. The observed interaction between MPs and microbiome has implications regarding the effect of ingested MPs on an organism's gut flora. It could serve as another means of harming an animal or human, as the gut microbiome is linked to the immune system.[68]

MP consumption affects aquatic wildlife and humans alike. Senathirajah and Palanisami found that the average person consumes up to a credit card's worth of plastic (5 g) per week.[69] Another study by Cox et al. found that the humans may ingest up to 39,000−52,000 particles annually (depending on age and sex) from seafood, sugars, salts, honey, and alcohol alone. When considering inhalation of MPs, the annual counts rise to 74,000−121,000 particles. Drinking only bottled water adds 90,000 particles annually, averaged across age and sex, while drinking tap water adds an average of 4,000 particles annually.[70] Additional evidence for the human consumption of MPs comes from Schwabl et al., who analyzed human excrement for MPs and confirmed their presence in the stool of all eight study participants.[71] Nanoplastics have even been detected and quantified in human blood.[72] The potential negative effects of MPs are not only relevant to wildlife either. Han et al. found that exposure to MPs made of polyvinyl chloride (PVC) and acrylonitrile butadiene styrene (ABS) at concentrations of 0.01 mg/mL to 1 mg/mL over 4 days caused human-derived cells to release interleukin 6 (IL-6) and tumor necrosis factor-α (TNF-α) proteins in an immune response.[73] Schirinzi et al. have demonstrated that human cerebral and epithelial cells exposed to low doses of polyethylene (PE) and polypropylene (PP) MPs (10 ng/mL to 10 μg/mL) undergo oxidative stress in the form of reactive oxygen species (ROS) generation.[74] There is growing evidence that nanoplastics can undergo cellular uptake in the lungs and gut.[75−78] The extent and implications of MP and NP bioaccumulation in humans should be more thoroughly investigated.

MP ingestion can be hazardous due to food dilution and physical damage to organisms.[50] The biofilms that grow on MP surfaces allow pollutants to become concentrated and can serve as vectors for harmful bacteria populations. There is even evidence that plastics (and other man-made debris) can transport invasive species across bodies of water.[79] The potential for MPs to cause harm to the environment, aquatic ecosystems, human health, and transmit illness must be further researched.

DETECTION, SEPARATION, AND QUANTIFICATION METHODS

The MP detection process consists of collection, separation, inspection, and finally quantification. According to an in-depth literature survey by Prata et al., the most common collection method used is nets, followed by pumps, and last sieves. Net mesh size can create wide variability depending on the pore size, with smaller pores leading to much higher collection concentrations.[80] For instance, plankton nets can recover MP concentrations 30 times higher than manta nets.[81] Nets and pumps allow for the collection of large water samples which leads to a more accurate and representative concentration.[80] Reducing the sample size can be done by filtering the larger initial water sample with decreasing steel meshes.[82] However, the issue of contamination arises as Nylon nets and pumps may lead to the addition of MPs to samples.[80] Sampling from lake sediment is also an option to test for MPs. Both water and sediment samples are affected by variability due to MP properties such as density, and environmental conditions such as winds and currents. However, sediment sampling can at least limit the variability due to humidity, which can impact water samples.[80]

Regarding separation, filtering or sieving is the most common method to initially separate MPs from water and sediment. Next, one can utilize density separation (flotation) by adding the sample to a salt-saturated solution. Sodium iodide (NaI) is perhaps one of the best options for this step, as it can be recycled for multiple cycles and does not harm the environment. However, it cannot be used with a cellulose filter as they can react to turn the filter black and make visual inspection difficult.[80] Oil can be added to salt-saturated solutions to improve recovery rates.[83] If instead elutriation is used, a liquid such as water is injected at the bottom of the sample inside a column, which takes advantage of the buoyancy of MPs to separate them from the sinking sediment.[84] Elutriation may allow for better representativeness because it is easier to use for larger volume samples.

The next step is the removal of organic matter, which helps to simplify the identification of MPs, as dark pieces of organic matter can be confused with MPs. Digestion of organic material can be achieved through oxidative, acidic, alkaline, or enzymatic methods. However, the acidic and alkaline methods may both damage or discolor the plastics, which can lead to inaccurate counts, especially when the quantification relies on visual inspection.[85] Enzymatic digestion effectiveness can vary but it is safer than acidic or alkaline digestion.[86] Hydrogen peroxide (H_2O_2) is an oxidizing agent which digests organic matter more efficiently than acids and bases, and does not damage the MPs.[87]

There are two main categories of detection methods: visual inspection and chemical characterization. Visual inspection entails the utilization of a stereoscope or microscope to find and quantify MP particles visually. However, this method is time-consuming and creates large sources of error because it is subjective. Thus, it is not recommended for particles smaller than <500 μm.[88] Visual inspection can lead to variances in total count as great as 40%, due to factors such as experience and fatigue.[89] Further, up to 70% of visually detected MPs may be other materials that are misclassified.[90] This is because it is difficult to discern actual MPs from organic materials. However, the advantages to this method include that it is widely accessible and allows the classification of MP particles by size, color, and shape which can help determine their origins. Also, staining the particles with dye, such as in Nile Red staining, can improve accuracy and result in recovery rates as high as 96.6%.[91]

Regarding chemical characterization, there are several commonly used methods. Fourier transform infrared spectroscopy (FTIR), Raman spectrometry, and thermal analysis as pyrolysis gas chromatography−mass spectrometry (py-GC-MS) are highly accurate, and FTIR and Raman can preserve the MP

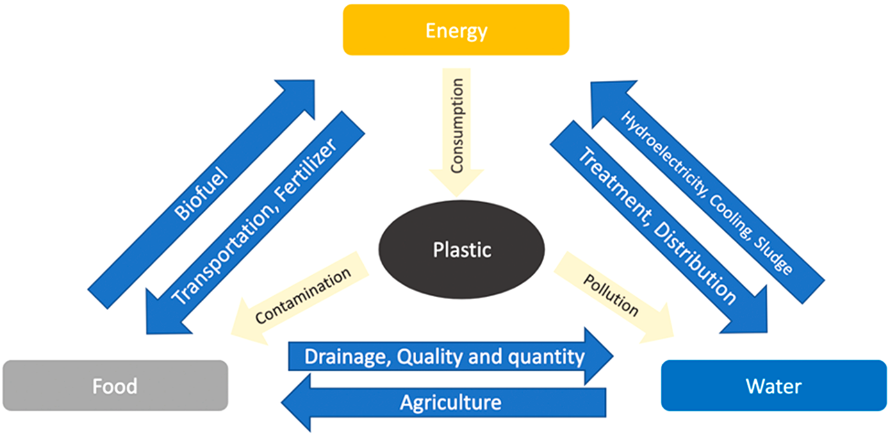


Figure 2. Food, Energy, Water, and Plastic nexus. Adapted with permission from ref 99. Copyright 2018 American Chemical Society.

particles. However, these methods are time-consuming, and require complex equipment and trained personnel. Also, FTIR can lose accuracy with particles under 20 μm, and the accuracy of Raman spectroscopy can be worsened by fluorescent pigments and additives. These drawbacks limit the widespread application of these methods and prevent on-site detection.[80] Scanning electron microscopy (SEM) analysis is helpful for discerning small plastic particles but is not appropriate for large samples. A novel detection device consisting of a portable optical sensor which can detect transparent and translucent MPs in water was developed in 2019.[92] However, there is still a need for widespread, portable, inexpensive, and accessible detection methods.

Standardization of collection and detection procedures would help to compare across different studies, as well as provide credibility to results. Prata et al. suggest defining a standard mesh size, minimum volume of water, a standard sediment sampling depth, and number of replicates that would provide sufficient representativeness.[80] Regarding sediment sampling, 11 samples per 100 m of beach can estimate MP concentration at a 90% confidence level.[93] The National Oceanic and Atmospheric Association (NOAA) recommends using 400 g per sediment sample, followed by drying and weighing,[94] while the Marine Strategy Framework Directive (MSFD) technical subgroup suggests using at least five replicates of the top 5 cm of sediment.[95] Standardization of separation and digestion procedures could include defining NaI as the standard for salt saturation or H_2O_2 as the standard for oxidative digestion. Regarding detection, standards for visual and chemical characterization could be defined as well.

Padervand et al. published a review of MP removal methods. They found that the most effective methods out of those reviewed are membrane bioreactors (>99%), conventional activated sludge (98%), wastewater treatment plants (>95%), and algae adsorption (94.5%).[18] Another highly effective method not included in the review is agglomeration-fixation by organosilanes (monomeric silicone-based chemicals)[96] which has an efficacy of up to 99.4%.[97] Although effective removal methods exist, some experts fear that MP removal from the environment is too gargantuan a task. The particles are extremely pervasive; they are present throughout bodies of water, soil, and even raining from the sky.[98] The best course of action may be preventative measures to stop their entrance into the environment in the first place.

FOOD, ENERGY, WATER, PLASTIC NEXUS

MPs play an important role in the food, energy, water nexus, and even the food, energy, water, waste nexus, as illustrated in Figure 2. Each aspect is integrally tied to one another.[99] First, fossil fuels are used to make plastics.[100] If the world aims to keep the global temperature from rising below 1.5 °C (as stated in the Paris Climate Agreement (2015)), then greenhouse gas emissions from the plastic lifecycle must be drastically reduced. If plastic production and incineration grow as planned, related greenhouse emissions could reach 1.34 gigatons per year in 2030. This equates to more than 295 new 500-megawatt coal-fired power plants. Plastic-related greenhouse emissions could reach over 56 gigatons in 2050, which is 10 to 13% of the entire remaining carbon budget for the planet.[100] The Center for Environmental International Law (CIEL) suggests several methods of lessening the contribution of plastics to climate change in a 2019 report. These suggestions include stopping production of single-use plastic, preventing development of new fossil fuel infrastructure, moving toward zero-waste communities, enacting extended producer responsibility, and creating ambitious goals for reducing greenhouse gas emissions from all sectors.[100]

The food industry also leads to greenhouse gas emissions,[101] and plastic is often used in food packaging. When food is wasted, both the food and plastic lead to greenhouse gas emissions and pollute the environment, either by sitting in landfills or through waste incineration.[100,102] Furthermore, plastic packaging is thought to be a net good as it can extend the shelf life of many food items. However, a 2018 report by the Friends of the Earth Europe found that although the amount of plastic packaging has increased since the 1950s in the EU, so has the amount of food waste. In certain situations, plastic packaging may actually serve to increase the amount of food waste that is generated, such as with convenience foods like precut produce and salads.[103] The report also gives recommendations on how to reduce plastic and food waste, which include investigating the causes of food waste and its intersection with plastic packaging, and investing in waste prevention systems.[103]

MPs are also presently tied to the food we consume because they are present throughout the food chain and are often consumed as a result of certain foods and drinks, bottled water versus tap water for example.[70] Furthermore, the greenhouse gas emissions from the food industry and plastic production contribute to climate change, which then causes more extreme weather patterns.[104,105] This sometimes leads to overflow events from flooding, which then contaminates surface waters with

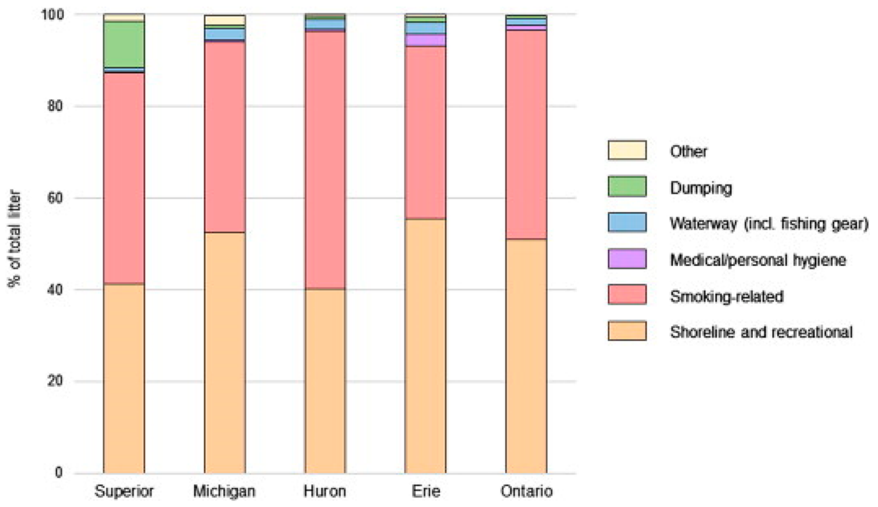


Figure 3. Percentages of litter items in the Great Lakes grouped according to activity on an item-by-item basis. Reprinted with permission from ref 42. Copyright 2015 Elsevier.

more MPs.[106] MPs consumed by plankton can also reduce their ability to remove CO_2 from the atmosphere.[107] The issue of macro- and microplastic pollution should be thought of as inherently tied to climate change and food security.

MP pollution and water quality are social inequality issues. A report published by the organizations Dig Deep and the U.S. Water Alliance analyzed quantitative national data from the American Community Survey (ACS) and the U.S. Census Bureau to characterize the water access gap in America.[108] The report found that race is the strongest predictor of water and sanitation access. Black and Latinx households are twice as likely to lack indoor plumbing and Native American households are 19-times as likely. Household income, education level, and unemployment rates are also predictors. Two million Americans live without running water and basic indoor plumbing, and many more without sanitation. Rural communities are also at risk, with 17% report having issues with safe drinking water. In some states, the number of people without access to indoor plumbing is increasing.[108] The Biden administration is focusing attention on the intersection of environmental protection and social justice with an executive order called Tackling the Climate Crisis at Home and Abroad (2021), which includes the creation of the government-wide Justice40 Initiative. This initiative aims to address environmental injustices, as well as deliver 40% of the overall benefits of environmental justice-related federal investments to communities that have been impacted disproportionately by health, environmental, economic, and climate issues.[109]

Plastic is inherently linked to energy, water, and food sectors. Thus, solving the issue of macro- and microplastic pollution will be crucial in remedying problems regarding food, water, and energy, such as water pollution, food contamination, and greenhouse gas emissions from plastic manufacturing and waste.

■ SOLUTIONS

Finally, potential remedies to the situation should be explored. There are several measures currently in place that protect the Great Lakes against MPs, but this protection could be more extensive. The Microbead-Free Waters Act signed by President Obama in 2015 prevents the sale of microbeads in "rinse-off" cosmetic products. However, this rule allows microbeads to continue to be used in other products such as lotion and makeup.[110] It also does not address larger plastic debris, which can degrade into MPs over time. Another measure that prevents plastic pollution in the Great Lakes is the Annex V of the Great Lakes Water Quality Agreement (GLWQA) which prohibits vessels from dumping any garbage into the lakes. However, this agreement does not cover the pollution originating from land. Some municipalities near the Great Lakes have prohibited smoking on beaches, potentially decreasing the amount of macroplastic entering the lakes which then degrade into MPs over time. Cigarette butts are made of cellulose acetate, a photodegradable but not biodegradable plastic. Littering of cigarette butts poses risks to the environment as they have collected the chemicals from smoking, and thus toxic-infused plastic fragments may persist.[111] A smoking ban on beaches may reduce plastic pollution, given that cigarette butts account for much of the litter on all Great Lakes shorelines, according to data from Adopt-a-Beach and Great Canadian Shoreline Cleanup in 2012 as shown in Figure 3.

Besides prohibitory measures to limit plastic pollution in the Great Lakes, there are also several ongoing projects to aid this effort. On the industry side, Operation Clean Sweep (OCS), which is run by the American Chemistry Council and the Plastics Industry Association, promotes best practices to help manufacturers prevent preproduction plastic such as pellets, flakes, and powder from entering waterways.[112] However, enrollment in this program is voluntary, and asking plastic manufacturers to hold themselves accountable is not an infallible system. NOAA created the Great Lakes Land-Based Marine Debris Action Plan (2014−2019) to address pollution in the Great Lakes. The plan was in collaboration between governments, researchers, NGOs, and businesses around the Great Lakes. After the completion of the plan, they have published an Accomplishment Report with their results.[113] Over five years, NOAA has conducted research and published scientific articles, guided management and policy makers, educated ∼180,000 people on plastic pollution in the Great Lakes, and removed 306,665 pounds of debris through volunteer efforts. Their plan included identifying research needs surrounding MP pollution in a workshop held by the International Joint Commission between the Canadian and US governments, the results of which are discussed in the following section. They have also created an online portal that summarizes different plastic-monitoring projects in the Great Lakes, several of which focus on MPs.[114]

As part of the plan, the City of Cleveland Mayor's Office of Sustainability and NOAA have coordinated a plastic reduction campaign called "Don't Break the Lake" regarding Lake Erie. The campaign included social media outreach, posting signage at water refill stations and grocery stores, mailed inserts in water bills, and giveaways of reusable items. The number of reusable bags used by customers have increased, according to preliminary data.[113] This result suggests that such campaigns can inspire behavioral changes, whether reusable bags are the solution or not. The campaign may have been aided by the issuance of a toolkit to volunteer advocates listing best practices for encouraging policy and management changes to limit plastic pollution, called "Plastic-Free Great Lakes: An Advocacy Toolkit to Make a Difference in Your Community" published in 2018 by the Alliance for the Great Lakes.[115] This toolkit discusses the effectiveness of different policy changes that have already occurred in response to plastic pollution in the Great Lakes, including the plastic bag fee in Chicago, community initiatives in Evanston, IL, and the refundable deposits on recyclable plastic items in Michigan and New York. The plastic bag fee in Chicago has led to a 40% decrease in the number of plastic bags used per shopping trip and a 20% increase in customers who use reusable shopping bags, according to preliminary results.[116] NOAA has now published a new five-year plan for 2020−2025, available for viewing on their website.[117]

Another effort focused on removing plastic pollution from the Great Lakes is spearheaded by the nonprofit organization Council of the Great Lakes Region (CGLR) called Great Lakes Plastic Cleanup, in which 26 debris removal devices were installed in marinas across the Great Lakes.[118] The EPA also has a Trash Free Waters (TFW) Program which is complementary to NOAA's Marine Debris program. It aims to reduce the amount of trash entering water bodies in the U.S., targeting zero trash in 10 years. To do this they will focus on U.S. and international litter prevention strategies, researching impacts of macro- and microplastics on water quality, environment, and human health, and building partnerships to encourage innovation in material reuse and packaging.[119]

There is currently limited regulation of the large-scale and systemic pollution originating from the plastic industry discharging waste. It is estimated that around 230,000 t of nurdles leak into the oceans every year.[120] However, the Plastic Pellet Free Waters Act introduced by Senator Dick Durbin in 2021, and other similar proposed legislation, would make the EPA responsible for preventing plastic pellets (nurdles) and other preproduction plastic from being discharged into waterways by facilities that make, use, transport, or package them.[121] The Clean Water Act could also be utilized more often to apply to plastic pollution.[122] Currently, California is the only state that has classified preproduction plastics as pollutants that must be regulated under the Clean Water Act.[123] Given the lack of extensive plastic pollution regulation on the industry side, the burden of responsibility is borne largely by the public. Plastic bag taxes and bans, plastic litter collection efforts on Great Lakes shorelines, and campaigns such as "Don't Break the Lake" attempt to encourage sustainable behavior.[113] The Alliance for the Great Lakes' advocacy toolkit further aims to raise community awareness of the issue of plastics pollution and encourages reaching out to legislators.[115] Novel research can be a catalyst for widespread behavioral and policy changes. For example, Dr. Imogen Napper's research group is credited for some of the fundamental research which led to an international legislation banning microbeads in certain cosmetic products.[124] Utilizing the findings others have published about microbead concentrations, nonprofit organizations 5 Gyres Institute and Story of Stuff Project led a #BeadFree campaign that included educating the public and persuading manufacturers to remove microbeads from products.[125] Future efforts to effectively limit plastic pollution are expected to increase in many directions.

■ FUTURE DIRECTIONS FOR REGULATIONS

Plastics can be helpful in achieving certain sustainability goals such as lessening food waste by lengthening shelf life and lessening fuel usage when transporting products due to its light weight in comparison to other materials. MPs can currently be viewed as a pollution prevention and waste management issue rather than something to be done away with entirely, especially because there are currently no detailed standards about different types of MPs.[126]

The NOAA Marine Debris Program hosted a Microplastics in the Great Lakes workshop, gathering experts from governmental, academic, and industry backgrounds which culminated in a report available online. They agreed on ten recommendations for the International Joint Commission between Canada and the United States (IJC) to inform their response to the issue of MP pollution in the Great Lakes. Some of these recommendations are to communicate research results to the public and decision makers, utilize education, policy, and market-based instruments to encourage pollution prevention, conduct risk assessments regarding ecological and human health, invest in solution-based research, determine the sources and fate of MPs in the Great Lakes through modeling, and adopt standardized sampling and analytical methods for measuring MPs.[127]

Several tools are available to address pollution prevention and reduction. Market-based instruments including bans and fees are effective, as it has been found that a fee for "bad" behavior may have a greater positive impact than a reward for "good" behavior, modeling loss aversion. In Montgomery County, Maryland, it was found that a 5-cent tax on disposable plastic bags resulted in a 42% decrease in customers who used plastic bags, while a 5-cent tax reward on reusable bag usage resulted in virtually no change in behavior. If each household in Montgomery County shopped once a week, this could lead to an annual decrease of 18 million plastic bags.[128] This information can be utilized when drafting policies meant to mitigate plastic pollution. Existing mitigation measures can also be further expanded, such as extending the Microbead-Free Waters Act to include more products than just rinse-off cosmetic products. However, environmental costs of these decisions should be explored so that they are most effective at protecting the environment.

The NOAA workshop also suggested classifying MPs as a chemical of mutual concern (CMC) in the Great Lakes Ecosystem under the Great Lakes Water Quality Agreement, which would mean the United States and Canadian governments would be required to look into reduction strategies.[127,129] Further, Gago et al. suggested that an International Legally Binding Instrument (ILBI) be drafted to regulate MPs around the globe.[1] This could standardize regulations and make enforcing regulations easier.[130] In June of 2021, the House Committee on Science, Space, and Technology: Subcommittee on Environment had a hearing on Defining a National "Oceanshot": Accelerating Ocean and Great Lakes Science and Technology. Although this effort mostly focuses on exploring and characterizing the entire ocean, plastic pollution likely plays a role in the Oceanshot. Dr. Robert Ballard, famed

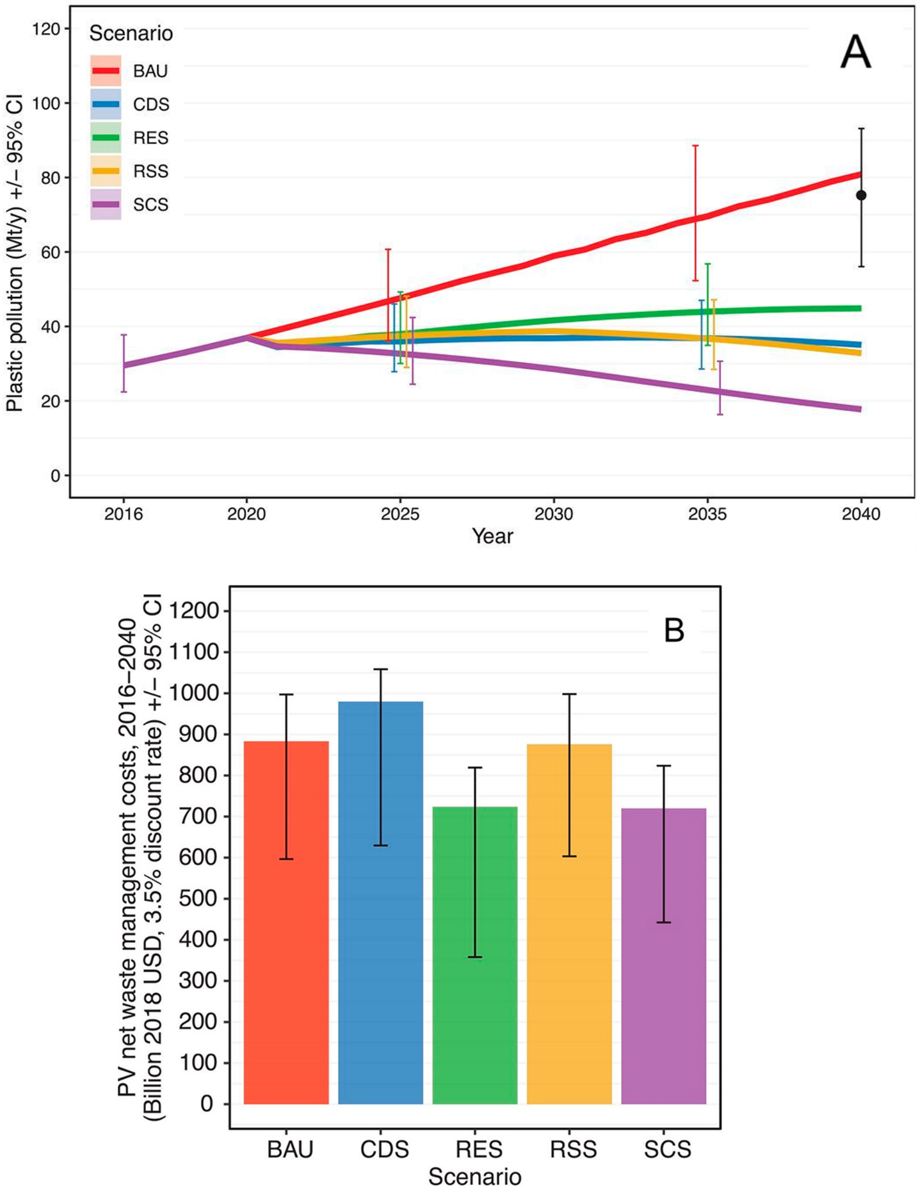


Figure 4. (A) Estimated annual rates of plastic pollution entering the environment in million metric tons/year ±95% confidence interval from each scenario from 2016 to 2040. The scenarios are Business as Usual (BAU), Collect and Dispose scenario (CDS), Recycling scenario (RES), Reduce and Substitute scenario (RSS), and System Change scenario (SCS). (B) Present waste management costs (collection, sorting, recycling, and disposal) in billion USD ± 95% confidence interval of plastic municipal solid waste by scenario from 2016 to 2040. Reprinted with permission from ref 150. Copyright 2020 AAAS.

ocean explorer and a witness to the hearing, expressed the potential of marine farming and protecting ocean life as well as expanding its productivity. Addressing the issue of plastic contamination in ocean crops will definitely play a role in realizing the concept of ocean agriculture.[131]

Moreover, the NOAA workshop recommended several pollution-prevention measures to the IJC. These include governments pursuing Polluter-Pays Principle and Extended Producer Responsibility (EPR) policies which would place the responsibility of dealing with plastic at its end-of-life stage on the manufacturers.[127] An example of this is a new law in Maine which requires manufacturers to pay the cost of recycling programs.[132] Another EPR program in Connecticut regarding mattresses, paint, electronics, and thermostat has mitigated more than 26 million pounds of waste since 2008, created more than 100 jobs, mitigated 13 million kg of carbon equivalent emissions, and resulted in a cumulative savings of $2.6 million per year for Connecticut municipalities.[133] Further, the EPR programs will likely not result in a rise in consumer prices. The Oregon Department of Environmental Quality of Canadian EPR programs concluded that prices had only risen by $0.0056 per item.[134] EPR measures could also demand that manufacturers bear the responsibility of adding filters to washing machines to collect microfibers from clothes before they pollute the environment.[127] Other methods of limiting MP entrance into water environments include the decentralized treatment of filtration at point sources.[135] Drain filters installed in plastic pellet factories would prevent preproduction pellets from entering waterways.[136] Talvitie et al. advise that filters capable of catching MPs or other advanced treatment methods can also be installed in more WWTPs.[137] Filters installed by gas stations or parking lots can also be used to collect MPs from road traffic in stormwater according to Fälström and Anderberg.[135]

Moreover, biodegradable plastics are a promising, but so-far incomplete solution to the plastic pollution problem. Biodegradable plastics are plastic that can be degraded into CO_2 and H_2O by biological forces such as enzymatic breakdown or metabolism by microorganism. Polylactic acid (PLA) and polyhydroxyalkanoate (PHA) are two common biodegradable polymers made from biobased feedstocks.[138] Biodegradable plastic and starch blends can be 70% starch by weight and still possess similar qualities as polymers, and are more cost-effective than other biodegradable plastics.[139] Although biodegradable and compostable plastic can be eventually broken down by microorganisms under specific conditions, such as specialized industrial composters,[140] many biodegradable plastics may never reach their desired end state, can contaminate batches of recycled plastic, and end up in landfills or litter the environment.[141−143] Biodegradable (especially oxo-biodegradable) plastics may simply degrade more quickly into MPs in the environment than traditional plastics because their degradation does not equate to full decomposition.[143,144] Further, biodegradable and conventional plastics may be similarly harmful to organisms, with 67% of both inducing toxicity (bioluminescence inhibition) in in vitro assays of bioluminescent bacterium *Aliivibrio fischeri*.[145] However, there are some environmental advantages to bioplastics. Biodegradable and compostable plastics made from plant-based chemicals can sequester CO_2 in the product over their lifetime.[146] Hypothetically, transitioning from conventional plastic to the corn-based PLA could reduce U.S. plastic industry greenhouse gas emissions by 25%, and if traditional plastics were instead produced through renewable energy, emissions could be reduced further. Bioplastics being produced by renewable sources may lead to near-zero carbon emission.[147] Nonetheless, if biobased plastic manufacturing is expanded to a global scale, this would require cropland expansion−competing with food production−and possibly deforestation. This potential deforestation, combined with the increased use of farm machinery which runs on petroleum, could increase carbon emissions.[140,141,146]

Conventional plastics can be better regulated when policy is informed by standards, which are currently lacking. While the Microbead-Free Waters Act banned all microbeads in rinse-off products, DeVitt et al. propose a new standard called "Ecocyclable" which would define environmentally safe MPs based on degradability, bioaccumulation, and toxicity. A standard like "Ecocyclable" could be adopted to properly classify safe and unsafe MPs, as this will only make it easier to enact legislation regulating MP usage and pollution going forward.[148]

Another interesting prospect for future plastics is utilizing artificial intelligence (AI) and machine learning (ML) to design novel polymers and simulate their behavior and properties, including their potential toxicity. Wu et al. were able to train an algorithm on existing polymeric properties data and design thousands of hypothetical polymers with promising thermal properties.[149] Perhaps AI could help design plastics that could be easily broken down into mixtures, monomers, or other useful products with little environmental impact.

Lau et al. modeled different scenarios for dealing with plastic pollution from 2016 to 2040. The "system change" scenario involved all eight proposed interventions: "(i) reducing plastic quantity in the system, (ii) substituting plastics with alternative materials and delivery systems, (iii) implementing design for recycling, (iv) increasing collection capacity, (v) scaling up sorting and mechanical recycling capacity, (vi) scaling up chemical conversion capacity, (vii) reducing post-collection environmental leakage, and (viii) reducing trade in plastic waste". Their results demonstrated that the system change scenario was the cheapest option over time and resulted in the least plastic pollution, reducing the rate of pollution by 78% compared to "business as usual" in 2040. However, it still resulted in 644 million metric tons of plastic pollution.[150] Figure 4 presents a future trajectory of plastic pollution as well as the management costs under various action scenarios. This analysis suggests that rapidly implementing promising alternatives with the aid of appropriate standards, regulations, and education could avoid the most serious impacts on the environment, the global economy, and human health.

Public perception of plastic pollution can have a major impact. The negative perception of microbeads helped get legislation passed to ban them, and campaigns such as "Don't Break the Lake" are proof that educating the public creates changes in behavior.[113] Thus, education on other aspects of plastic pollution can have a huge impact as well. For example, educating the public about other sources of MPs such as clothes washing can promote more sustainable behavior such as washing fleece clothes less or hand washing.[6,113] Education on plastic pollution originating from discarded trash may also help reduce littering, especially on beaches. Similar to how pictorial health warning labels on cigarette packages are effective at lowering smoking rates and increasing quit attempts,[151] signage posted at beaches or in stores may help the public make choices that avoid MP pollution. Labels on products that release MPs into the environment may be effective at reducing their pollution by inspiring changes in consumption habits. Education campaigns could increase public investment in sustainable plastic products. There are many possible avenues to limit future plastic pollution in the Great Lakes. These would require a united effort by government leaders, businesses, and the public in moving toward this goal.

■ CIRCULAR ECONOMY

Plastic pollution is an expensive problem. Plans to tackle litter in the Great Lakes could cost around $468 million annually.[42] According to an analysis conducted by Beaumont et al. (2019), plastic in marine environments results in a 1−5% decrease in marine output which corresponds to a $500−2,500 billion loss of benefits originating from the marine ecosystem annually. This means that the annual cost associated with each ton of plastic pollution is between $3,300-$33,000. The 18 metrics used to quantify marine output included not only wild food output but also water conditions, entertainment, and mediation of wastes.[152] Similarly, some value must be lost due to plastic pollution in the Great Lakes.

The issue of plastic pollution can be mitigated by investing in solutions that will lead us closer to a plastic circular economy (Figure 5). The Ellen MacArthur Foundation hosts a network of businesses, cities, governments, universities, and leaders to foster a circular economy. They define a circular economy as one "based on the principles of designing out waste and pollution, keeping products and materials in use, and regenerating natural systems".[153] The foundation has an initiative focused on plastic recycling called New Plastics Economy which connects more than 1,000 organizations. The initiative is founded on three actions: Eliminate, Innovate, and Circulate to limit the amount

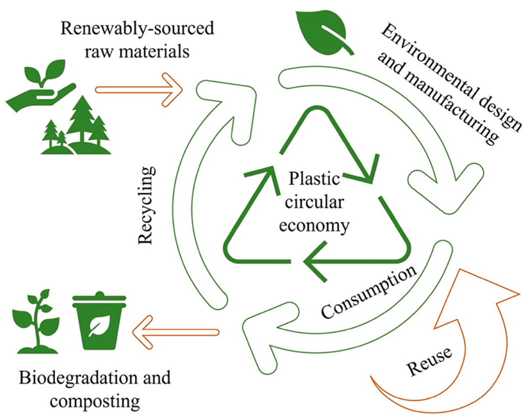


Figure 5. Circular economy for plastic, in which renewably sourced virgin feedstock is utilized in the design and production of reusable plastic products. The plastic products can be used, reused, and either recycled to become similar-quality plastic or anaerobically digested and/or composted.

of plastic used, develop more sustainable plastics, and recycle as much plastic as possible.[154]

Currently, most plastics are not recycled, and those that are recycled are downcycled to produce lower quality plastics through mechanical recycling. If plastics were recycled to produce more of the same high-quality plastics, as much as \$80-\$120 billion that is currently lost through single-use plastic packaging material annually could be gained back.[155] There already exist efforts to industrialize chemical recycling processes which can achieve this. For example, Loop Industries claims the ability to break down PET into monomers and then repolymerize to produce virgin-quality PET.[156] Companies like L'Oreal and PepsiCo have signed contracts to use their recycled PET.[157,158] A team at Lawrence Berkeley National Laboratory has developed a plastic called PDK (poly diketoenamine) which can be recycled without lowering its quality, as it can be broken down into monomers and separated from all additives simply by submerging in strong acid. Although the initial production of PDK is more expensive and carbon-demanding than conventional plastics, the recycling process of PDK is competitive with conventional plastics. Conventional plastics PET and HDPE cost less than \$1 per kg to produce and result in 2.73 and 1.9 kg of CO_2 emissions, respectively. Although recycled PDK could be made for \$1.50/kg, it would lead to only 1.6 kg CO_2/kg.[159]

Upcycling of plastics is another area of research that could help limit plastic waste and move toward a circular economy. Catalysis can be utilized to break down reclaimed PET into value-added products.[160] For example, a team of scientists headed by Dr. Massimiliano Delferro of Argonne National Laboratory has been able to convert single-use polyethylene (PE) into value-added products such as lubricants and waxes. This is done by a catalysis reaction called hydrogenolysis.[161] Certain enzymes isolated from bacteria are also capable of degrading plastics, and can be utilized in future plastic recycling and upcycling processes.[162]

Truly infinite recycling and upcycling of materials may be impossible due to the laws of thermodynamics, which posit that if entropy is lost somewhere in the universe, energy must be invested to do this, and that entropy is gained to an equal or greater amount elsewhere.[163] Although a closed loop with no losses may never be achieved, moving closer to a circular economy by recycling materials and limiting pollution will still be progress.

Realizing a circular economy for plastics will require policy changes and plastic industry regulation. The Ellen MacArthur Foundation created the Plastics Pact Network which connects initiatives involving organizations, businesses, NGOs, governments, and citizens across the world with the purpose of moving toward a plastic circular economy. Countries with national pacts include the UK, France, Chile, The Netherlands, South Africa, Portugal, the US, Poland, and Canada. Regional pacts include the European Plastics Pact and the Australia, New Zealand, and Pacific Islands (ANZPAC) Plastics Pact.[164] The Ellen MacArthur Foundation also created the Global Commitment to moving toward a circular economy which more than 500 organizations have joined, the companies among them producing 20% of all the world's plastic packaging. These brands and retailers have utilized more recycled plastic since joining the Global Commitment,[165] and have been able to collectively reduce their virgin plastic use by 2% since 2018, with projections to decrease by an additional 17% by 2025. But voluntary measures will not be enough to reach a circular plastic economy as quickly as necessary. A first step was taken at the United Nations Environmental Assembly (UNEA 5.2) in March 2022, where 175 countries adopted a resolution called End Plastic Pollution: Toward a legally binding instrument. This would compel the International Negotiating Committee (INC) to develop a legally binding UN Treaty addressing the full life cycle of plastics by 2024. In the future, there should be more policies that support a circular economy adapted to regulate the plastic industry.[166]

■ CONCLUSIONS AND FUTURE OUTLOOK

MP pollution is a multifaceted issue tied to food, water, and energy, posing threats to aquatic environments and health of all organisms. The presence of MPs in the environment taints water quality, contaminates food sources and products,[70] and correlates to fossil fuel emissions through its manufacturing and pollution.[100] Moving toward the goal of a circular economy will be helpful in limiting the introduction of MPs into the environment. Collaborative efforts from government, industry, and the public will be required to derive solutions that effectively limit the entrance of MPs into the Great Lakes and other water bodies.

More studies need to be conducted to gather data on MP concentrations in the Great Lakes to gain a better understanding of the sources and fate of MPs. Further research can be done to determine the rate at which micro- and macroplastics are degrading in the Great Lakes and what types of degrading effects are most impactful. The distribution and transportation of MPs throughout the Great Lakes should be more thoroughly investigated. Optimal sampling and quantification methods should be standardized to allow for comparison across studies. Standards regarding what constitutes environmentally safe MPs should be agreed on as well so that policies can be drafted with proper background information.[148] The pervasiveness of MP contamination throughout Great Lakes food webs should be further explored. Laboratory experiments should be conducted to investigate effects of MPs on the health of Great Lakes wildlife, paying attention to polymer, shape, and size of particles. The extent of human MP consumption through drinking water sourced from the Great Lakes should be quantified, and the human health implications should be further characterized. These studies will inform future risk assessments regarding MPs.

These research efforts and quantitative risk assessments may help motivate policy changes that prevent the production of MPs to begin with, as well as garner public interest in the cause of limiting MP pollution. With regards to policy, more should be done to limit the entrance of MPs into the Great Lakes, paying most attention to areas with highest MP counts such as regions closest to cities, where more particles are likely to enter the lakes.[167] The beach cleanup efforts that take place around the Great Lakes unfortunately cannot efficiently remove MPs, and only collect from the shoreline. Actions such as equipping more WWTPs whose effluents feed into the Great Lakes with the advanced filtration systems to effectively remove MPs from influents could reduce inputs. Smoking bans on more public Great Lakes beaches, as has already been banned in multiple Michigan cities, to limit plastic litter that will degrade into MPs over time could also be beneficial.[168] Effective EPR regulations could limit MP pollution from manufacturers. Campaigns aiming to educate the public on plastic pollution in the Great Lakes could lead to widespread behavioral changes.[113] The pervasiveness of MPs in the Great Lakes must be remedied quickly and robustly to preserve the ecosystem and protect the health of wildlife and human inhabitants.

AUTHOR INFORMATION

Corresponding Author

Junhong Chen – *Pritzker School of Molecular Engineering, The University of Chicago, Chicago, Illinois 60637, United States; Chemical Sciences and Engineering Division, Physical Sciences and Engineering Directorate, Argonne National Laboratory, Lemont, Illinois 60439, United States;* orcid.org/0000-0002-2615-1347; Email: junhongchen@uchicago.edu

Authors

Claire Fuschi – *Pritzker School of Molecular Engineering, The University of Chicago, Chicago, Illinois 60637, United States*

Haihui Pu – *Pritzker School of Molecular Engineering, The University of Chicago, Chicago, Illinois 60637, United States; Chemical Sciences and Engineering Division, Physical Sciences and Engineering Directorate, Argonne National Laboratory, Lemont, Illinois 60439, United States*

Margaret MacDonell – *Environmental Science Division, Computing, Environment, and Life Sciences Directorate, Argonne National Laboratory, Lemont, Illinois 60439, United States*

Kurt Picel – *Environmental Science Division, Computing, Environment, and Life Sciences Directorate, Argonne National Laboratory, Lemont, Illinois 60439, United States*

Maria Negri – *Environmental Science Division, Computing, Environment, and Life Sciences Directorate, Argonne National Laboratory, Lemont, Illinois 60439, United States*

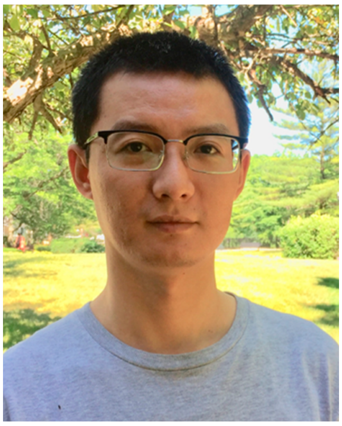
Complete contact information is available at: https://pubs.acs.org/10.1021/acssuschemeng.2c02896

Notes

The authors declare no competing financial interest.

Biographies

Claire Fuschi holds a B.S. in Molecular Engineering from the University of Chicago. She joined Professor Junhong Chen's research group in the second year of her undergraduate degree. Her research in the Chen Group investigates the intersection of water and public health.



Haihui Pu received his Ph.D. from the University of Wisconsin Milwaukee in 2015. Before joining the University of Chicago as a Staff Scientist, he completed a Postdoctoral Appointment at University of Wisocnsin-Milwaukee (UWM) and worked as a Sensor Scientist for NanoAffix Science, LLC. Pu received his M.S. degree from Fudan University and his B.S. degree from Nanjing University of Science and Technology in China. His research focuses on the first-principles/molecular dynamics simulations and statistical thermodynamics modeling on novel two-dimensional nanomaterials for environmental and energy applications, which include field-effect transistor nanosensors for detecting various target analytes of interest and energy storage devices.

Margaret MacDonell heads the Radiological, Chemical, and Environmental Risk Analysis Department in the Environmental Science Division of Argonne National Laboratory. She received her B.S. in biology and M.S. in civil/environmental health engineering (CE/EHE) from the University of Notre Dame, and her Ph.D. in CE/EHE from Northwestern University. Her research focuses on mixed environmental exposures, joint toxicity, and cumulative risk analyses with recent applications emphasizing sustainability, resilience, and responsible innovation for the circular economy. She is a Fellow and past President of the Society for Risk Analysis, a Fellow of the Waste Management Symposium, and senior scientist in the University of Chicago Consortium for Advanced Science and Engineering.

Kurt Picel received his B.S. in Chemistry from Western Michigan University in 1976 and his Ph.D. in Environmental Health Sciences from the University of Michigan in 1985. His research focusses on environmental and human health risks of chemical and radiological releases as well as on broader environmental risks from energy and industrial projects and processes including the lifecycle risks from plastics.

Maria Negri is the Director of the Environmental Science (EVS) Division at Argonne national Laboratory. She earned her Dottore in Scienze Agrarie Degree (Agricultural Sciences) in 1981 at the University of Milan in Milan, Italy. Her research to integrate bioenergy within working agricultural landscapes addresses the food, energy, water, and land nexus. In her more than 30 years as a scientist at Argonne, she conducted and directed laboratory to full-scale multidisciplinary projects developing technologies and concepts for environmental remediation and stewardship including soil remediation and water treatment. She has researched sustainable technologies for the environmental improvement of urban and agricultural processes.

Junhong Chen is currently a Crown Family Professor of Molecular Engineering at Pritzker School of Molecular Engineering at the University of Chicago and lead water strategist at Argonne National Laboratory. He received his Ph.D. in mechanical engineering from the University of Minnesota in 2002. His research interest lies in molecular engineering of nanomaterials and nanodevices, particularly hybrid nanomaterials featuring rich interfaces and nanodevices for sustainable energy and environment. His approach is to combine multidisciplinary experiments with first-principles calculations to design and discover novel nanomaterials for engineering various sensing and energy devices with superior performance.

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