



## How to protect water sources from microplastic contamination?

Muhammed Atamanalp<sup>1</sup> • Dilek Türker<sup>2</sup>

<sup>1</sup> Department of Aquaculture, Faculty of Fisheries, Atatürk University, Erzurum 25240, Türkiye

<sup>2</sup> Department of Biology, Faculty of Science & Art, Balıkesir University, Balıkesir 10020, Türkiye

### Correspondence

Muhammed Atamanalp; Department of Aquaculture, Faculty of Fisheries, Atatürk University, Erzurum 25240, Türkiye

✉ [mataman@atauni.edu.tr](mailto:mataman@atauni.edu.tr)

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### Abstract

Microplastics (MPs) have emerged as one of the most widespread and persistent pollutants of the 21st century, posing profound challenges to aquatic ecosystems, biodiversity and human health. Derived from both primary and secondary origins, MPs are leaching into aquatic systems through synthetic textiles, vehicle components, personal care products and domestic wastewater discharge. Once in aquatic environments, they exhibit high chemical stability and adsorptive capacity, acting as vectors for persistent organic pollutants (POPs), heavy metals and pathogenic microorganisms. The resulting bioaccumulation and biomagnification across trophic levels causes cellular oxidative stress, immunotoxicity, endocrine disruption and reproductive impairment in aquatic organisms, thus extending ecological risk to humans through trophic transfer. This compilation of recent studies concludes that the MP crisis is not only an environmental problem but also a systemic reflection of unsustainable production and consumption patterns. Addressing this challenge requires global cooperation, integrating scientific expertise with socio-political action and redefining economic growth within the limits of planetary health. This review examines the multidimensional nature of MP pollution, its sources, pathways and impacts on environmental integrity, while proposing strategic frameworks for the protection of global water resources.

**Keywords:** bioremediation; ecotoxicology; environmental health; microplastics; preventive strategies; water pollution

### 1 | INTRODUCTION

In the last fifty years, plastic materials have replaced more environmentally friendly materials such as glass, metal and wood in many application areas due to their various advantageous properties and have become indispensable in every field of mankind (Feil and Pretz 2020).

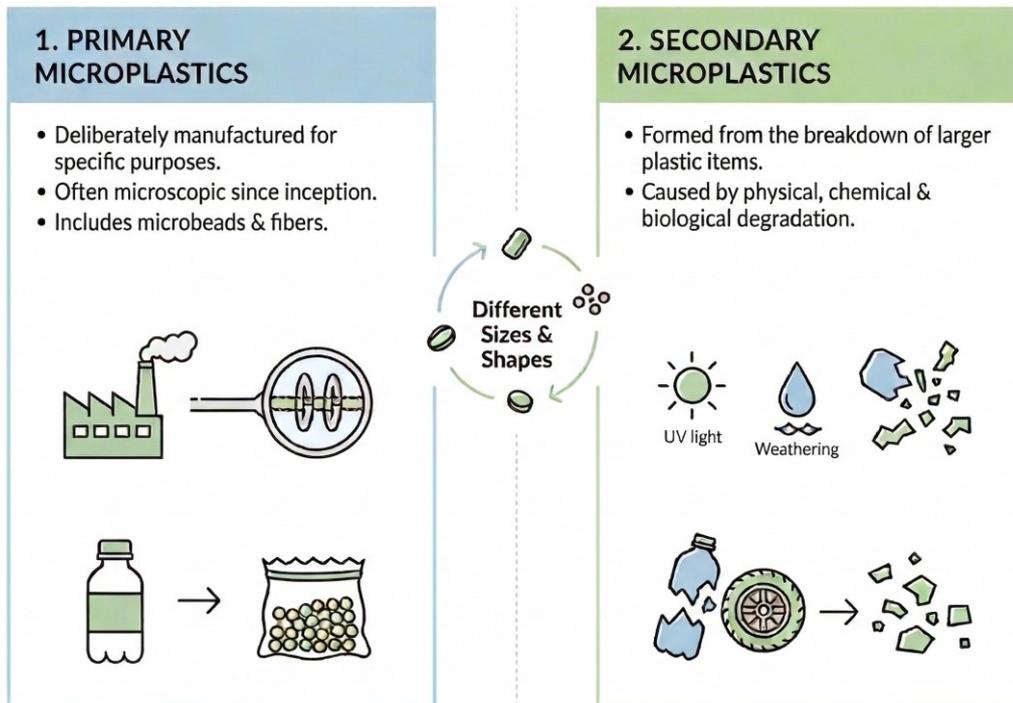
Plastics are widely used in different sectors and found indifferent areas of daily life due to their flexibility and durability properties (Adam *et al.* 2021). In addition to these features, the production of plastics increases even more due to the fact that they are significantly more economical than other materials and disposable materials

that contribute to the rhythm of accelerating daily life. While the annual global plastic production amount was 1.5 million tons in the 1950s, this figure is estimated to reach 1800 million tons in the 2nd quarter of the 21st century (Köktürk *et al.* 2024).

The term 'plastic' is originated from the Greek word 'plastikos', meaning 'moldable' (Okan *et al.* 2018). Due to limited recyclability of discarded materials and inadequate preservation processes, plastic debris accumulates in the environment. Due to the limited recyclability of waste materials and inadequate preservation processes, plastic waste accumulates in the environment. Recently,

research on environmental impacts of plastic has acquired a new dimension through the discovery and study of microplastic (MP) particles often defined as smaller

than 1 mm, but that are often in the range of several micrometers (Cole *et al.* 2011; Figure 1).



**FIGURE 1** The specifications of primary and secondary microplastics.

Plastics are classified according to their chemical structures, polarities and applications. The most commonly used synthetic polymer classes in industrial applications are polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET) and polyvinylchloride (PVC). For this reason, it is widely distributed in marine and coastal environments worldwide. Much research has been found in the ecotoxicology field on other types of MPs, such as PP, polyester (PES)/PET, PVC, polyamide (PA), acrylic, polyether, cellophane and polyurethane (Atamanalp *et al.* 2025). Particularly in the aquatic ecosystem, the most investigated MP types are PE and PS (Alak *et al.* 2022; Atamanalp *et al.* 2025).

The persistence of plastics in the environment has been estimated to range from several decades to centuries. Their strong resistance to degradation results in a prolonged half-life; making plastics remarkably durable a characteristic that, while beneficial for usability, also contributes to the long-term accumulation of MPs (Alak *et al.* 2022). Plastic pollution poses significant ecological and economic challenges: it not only reduces the visual appeal of aquatic environments but also endangers biodiversity, as aquatic species can easily ingest plastic particles. Moreover, plastics can act as carriers of various chemicals, including additives and waterborne contaminants (Atamanalp *et al.* 2025). Plastic pellets, in particular, have a strong tendency to adsorb hydrophobic pollutants and subsequently release them into ecosystems or organisms through desorption processes (Bellasi *et al.* 2020).

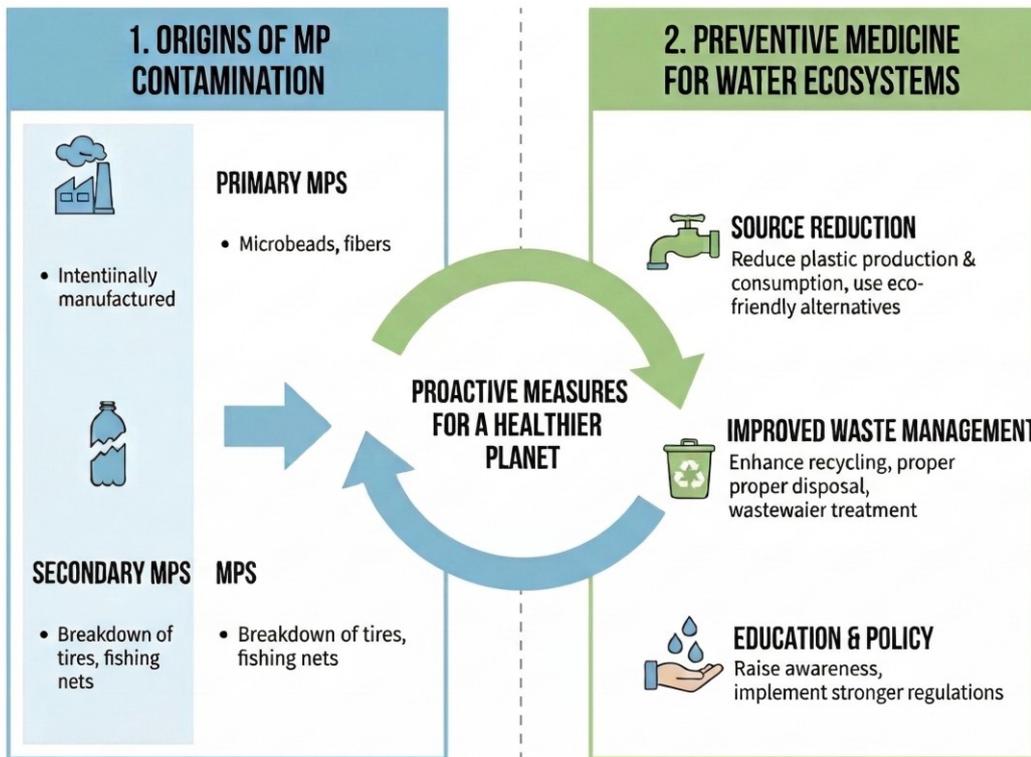
Aquatic ecosystems are dynamic structures such as seas, rivers, wetlands and lakes that differ from each other. This diversity also leads to differences in their responses to pollutants, making it difficult for researchers. In addition, factors such as population density, industrial production, mining facilities or highways in their surroundings also create differences in the definition of the internal structures of these ecosystems. All these variables, coupled with the high diversity of pollutant types, necessitate a much higher number of studies in this field (Köktürk *et al.* 2024).

Recognizing that MPs are a significant threat to the ecosystem, the scientific world is now intensively investigating what measures can be taken to address this threat. However, considering the size and chemical structure of MPs, it is known that it is not easy to get rid of these structures. Attempts have been made to remove MPs from the ecosystem through innovative MP removal strategies and technologies such as nanoparticles, micro-organism-based remediation and tertiary treatment, but these methods have not been able to eliminate MPs or transform them into a less harmful form (Ahmed *et al.* 2024; Köktürk *et al.* 2024).

Studies have reported that MPs can enter the human body by ingestion, respiration and dermal route. So the complete eradication of MPs is especially important for humans and the tissues and organs of other living organisms (Rahman *et al.* 2021; Zhao *et al.* 2024; Alpaydın *et al.* 2024).

Plastic derivatives, which cause multifaceted and long-term damage to the environment and human health but cannot be abandoned, reach aquatic resources in different ways. At this stage, researchers should concentrate on discussing the measures to be taken before the

problem occurs with the logic of "preventive medicine" (Figure 2). This review focuses on MP's occurrence in daily life, transmission routes, adverse effects on water resources, and ways to protect resources.



**FIGURE 2** Protecting our water ecosystems: a "preventive medicine" approach against microplastic contamination.

## 2 | Microplastic and water sources

### 2.1 What is microplastic (MP)?

Plastics are divided into various groups (megaplastics, macroplastics, mesoplastics, MPs, and nanoplastics) according to their size (mm,  $\mu\text{m}$ ) (Kershaw *et al.* 2019). In addition, depending on the way they are produced, these MPs can be grouped into primary and secondary MPs and come in different sizes and forms (Figure 1). Primary MPs are intentionally produced for specific purposes, including the production of plastic products or applications such as personal care products (Sun *et al.* 2023). Secondary MPs are formed because of physical, chemical, and biological degradation of larger plastics. The breakdown of large plastic fragments into smaller particles through various forces results in the formation of secondary MPs (Salerno *et al.* 2021).

It is often very difficult, sometimes even impossible, to determine the exact source of MPs detected in the environment (An *et al.* 2020). Because of this difficulty, researchers working on this issue focus on the negative effects it causes in organisms rather than this part of the problem. The involvement of aquatic toxicologists as well as other disciplines in these researches and the establishment of studies on the origin of MP contamination

and the protection of aquatic ecosystems beforehand by taking measures in the style of "preventive medicine" will have more effective results in terms of the environment.

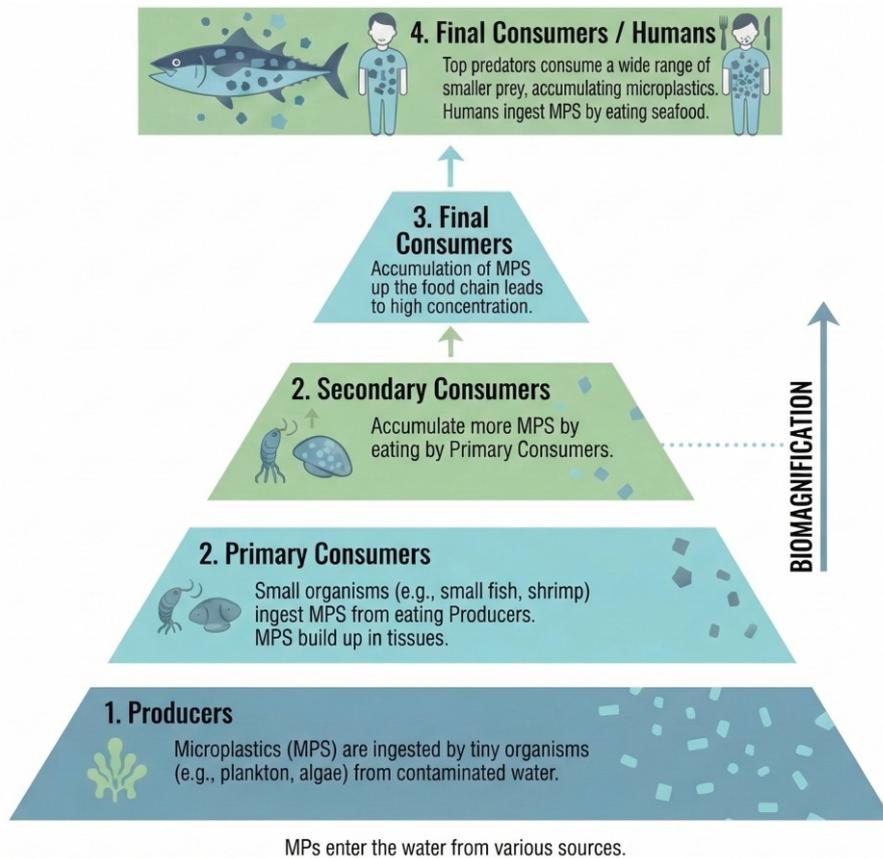
While their "micro" designation makes them seem innocent, the damage they cause to aquatic ecosystems is unfortunately "macro" in scale. These microscopic particles have a multifaceted negative impact on aquatic organisms. These effects have direct adverse effects such as congestion in the gills and gastrointestinal tract and damage to these organs from the corners of the particles. In addition, there are indirect harmful effects such as mistaking MPs for food, ingesting them into their bodies and causing false satiety (Alak *et al.* 2022; Figure 3).

For practical purposes, MPs are defined as synthetic organic polymers (hereafter, plastics) in the size range of 0.001 – 5 mm (GESAMP 2015). MPs have been detected in air, soil, fresh water, drinking water, the oceans, aquatic and terrestrial biota, food products, and human placenta and stools (Nor *et al.* 2021; Atamanalp *et al.* 2021; Alak *et al.* 2023).

MPs present a new set of issues, because of two main reasons: (i) they are small enough to be taken up by biota and thus can accumulate in the food chain; and (ii) they can sorb pollutants on their surfaces, thus enriching

them on these particles. Therefore, this situation can cause double-sided damage. To explain this briefly, MP, which is included in the metabolism of every living creature in the water, is present in much larger amounts in the other creature that feeds on it, which can have fatal consequences (Atamanalp *et al.* 2022a, 2022b).

The formation and accumulation of MP materials in living organisms have been studied almost exclusively in marine and freshwater ecosystems. (Browne *et al.* 2011; Ashry and Al Naggar 2025; Deswati *et al.* 2025; Drova *et al.* 2025; Du *et al.* 2025; Noor *et al.* 2025; Shakik *et al.* 2025; Siddiqa *et al.* 2025; Zhou *et al.* 2025).



**FIGURE 3** Microplastics (MPs) in the food chain: accumulation and magnification.

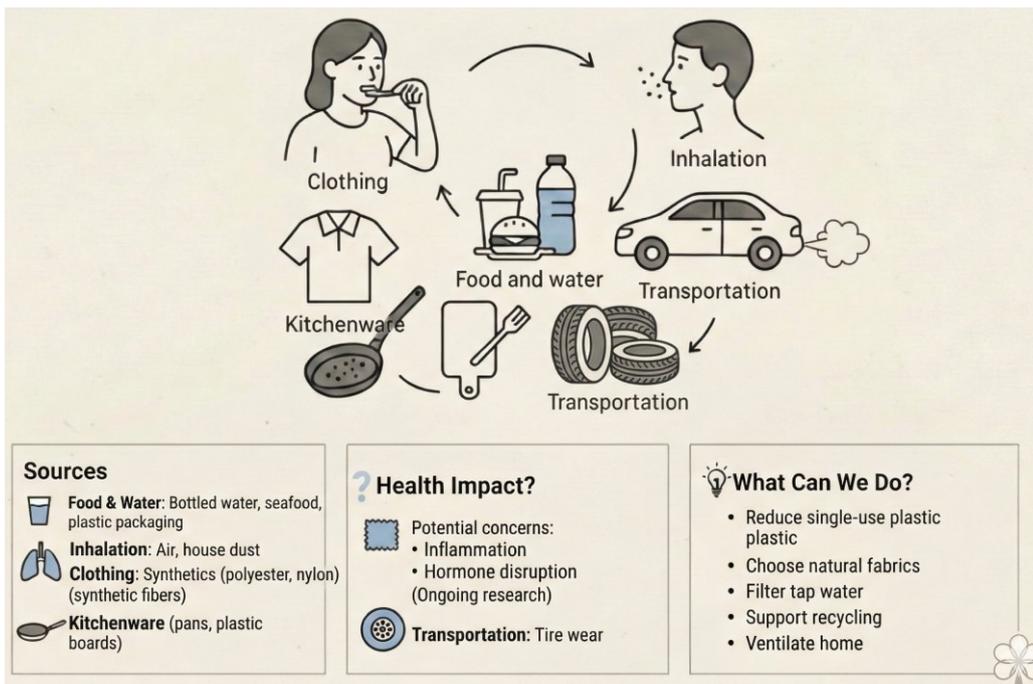
## 2.2 Daily life and MP sources

Every moment of daily life, almost every activity we do while living constitutes a resource for MP production. Personal care products, especially the toothpaste/toothbrush we use when we start the day in the morning, the clothes we wear, the disposable containers we put our drinks and food in, and the tires of the vehicles we use for transportation afterwards are the components of life that are waiting to bring MPs together with our environment and cannot be given up for the people of our age. Microplastics (MPs), especially the so-called "primary microplastics", are natural components of many consumer goods we use.

Particles smaller than 5 mm in size, we eat, drink and even breathe MPs throughout the day. Kitchen life, which has an important place in people's daily lives, is one of the important sources of MPs (Figure 4). Common kitchen items like nonstick pans, plastic chopping boards, and disposable cutlery are made of plastics prone to degradation, especially under the influence of factors like

temperature, wear, and mechanical damage (Liu *et al.* 2024). Drinking water, including tap and bottled water, is the largest source of plastic in our diet, with the average person consuming about 1,769 tiny MP particles each week, according to a 2019 report supported by WWF (De Wit and Bigaud 2019). The fact that this is the case with drinking water, the most basic foodstuff, is important in terms of showing the gravity of the picture.

Another important source is the textile industry, where synthetic clothes, which are preferred for their comfort and ease of use in modern life, cause MPs to be transported into our bodies through inhalation. Another environment where MP abundance is seen, especially in hot seasons with the effect of the sun's rays, is automobiles, since almost all their interior parts are made of plastic derivatives, allowing people to carry large amounts of these particles. When all these stages of daily life are analyzed, it is seen that our life is plasticized and because plastics are in almost every part of modern life, it's extremely difficult to eliminate exposures (Liu *et al.* 2024).



**FIGURE 4** Microplastics (MPs) exposure is a daily threat.

### 2.3 What are the ways of MP contamination to water sources?

Single-use plastics (e.g., packaging) constitute just under 50% of total global plastics manufacture (Geyer *et al.* 2017) and are well-recognized contaminants in outdoor environments. However, about half of plastics manufactured are intended for longer-term applications, such as in building construction, furniture, carpeting, electronics/electrical components, clothing, and vehicle parts and accessories (Hale *et al.* 2022). These uses are important to consider as they often employ plastics with higher levels of toxic additives (e.g. flame retardants) and may be in close and prolonged contact with human receptors (Hale *et al.* 2020). Plastics also are used as surface coatings (such as vessels, building, and road marking paints) and water-proof barriers on paper products, e.g., beverage cups. Such materials may release micro- and nanoplastic particles (Zangmeister *et al.* 2022). In recent years, products such as inexpensive, single-use sachets containing small servings of personal care and cleaning goods, beverages, and food have been aggressively marketed in developing nations, opening a growing market. MPs are entering our lives increasingly each day.

The contamination of aquatic systems with plastic debris is an emerging environmental crisis with studies regularly describing its ubiquitous environmental presence (Eriksen *et al.* 2014; Hoellein *et al.* 2014; Jambeck *et al.* 2015) and the effects on aquatic organisms (Browne *et al.* 2008; Farrell and Nelson 2013; Setala *et al.* 2014; Hall *et al.* 2015). The increasing rate of use of plastics increases the formation of MP and contributes to its contamination of water resources.

As in other ecosystems, the most important factor in

the transmission of microplastics (MPs) to aquatic ecosystems is the size of the particles. As we move towards micro and nano dimensions, contamination and spread are much faster and more widespread. Given the wide range of products and activities that generate MPs, the likelihood of contamination in potable water is considerably high. The small size ( $\leq 5$  mm) and low density of MPs facilitate their extensive dispersion, transport, and distribution over long distances within various environmental media (Eriksson *et al.* 2013).

Nearly 80% of marine plastic pollution originates from activities on land, whereas the fishing industry contributes around 18%. Wind and rainfall also transport plastics to the oceans, where they gradually break down into smaller fragments through processes such as photo-oxidation and mechanical abrasion. In recent years, medical wastes—especially disposable masks and surgical gloves—have emerged as notable sources of MPs, a problem that intensified during the global COVID-19 pandemic. Major routes of MP contamination in nearby environments include agricultural practices, river and coastal runoff, and various human-driven activities like tourism and transportation occurring over different spatial scales. It is estimated that billions of micro- and nanoplastic particles enter aquatic systems solely from discarded face masks. As the size of these particles decreases, their potential for bioaccumulation increases, creating significant risks to aquatic organisms, the food web, and ultimately human health. Moreover, the development of biofilms on MP surfaces increases their mass, facilitating faster descent through the water column (Patidar *et al.* 2023).

MP pollution in drinking water represents a more critical threat than that from fish or seafood, as the

amount of water consumed each day far exceeds seafood intake, and the route from the source to the tap involves fewer stages of filtration or dilution (Oladoja and Unuabonah 2021).

Most of the plastic-derived pollutants found in rivers, seas and oceans originate from large plastics coming from land. These large masses of plastic break down into MPs under the influence of wind, waves and sunlight and reach rivers and seas and then oceans. In marine and ocean environments, waves and ultraviolet rays act together to break plastics into small particles, so the process is faster. A similar situation is observed in rivers depending on the increase in water flow rate. In lakes where water movement is limited, large plastics tend to settle to the ground, where they experience the process of decomposition into particles depending on sediment conditions. As can be seen, the transformation of plastics into MPs is a process directly related to the nature of the aquatic ecosystem, and their storage in the environment is also determined by these conditions.

#### 2.4 What are the negative effects of MP in water resources?

Microplastics (MPs) pose very different challenges compared to other pollutants due to their structural characteristics. These challenges begin even at the sampling stage of these chemicals from water. The main challenges in sampling are representativeness and completeness. First, MPs are not homogeneously distributed in the water column but vary depending on the characteristics of the MPs (density, shape, size) and environmental variables (water type, currents, waves) (Pico and Barcelo 2019).

MPs that reach water resources through different routes cause negative impacts on aquatic ecosystems in many ways (Figure 5). Once MPs are introduced into the aquatic system they demonstrate complex interaction with organisms and accumulate and are retained in tissues (Ziani *et al.* 2023). In macro-components of aquatic ecosystems, these effects are better characterized because they are visible. Impacts in higher groups of organisms have been recorded more often because they are more conspicuous in this respect. Among these living groups, there are many studies, especially on fish. Both marine (Atamanalp *et al.* 2021; Noor *et al.* 2025; Drova *et al.* 2025; Du *et al.* 2025) and freshwater fish species (Atamanalp *et al.* 2022; Ashry *et al.* 2025; Deswati *et al.* 2025; Shakik *et al.* 2025; Siddiqi *et al.* 2025; Zhou *et al.* 2025) - MP interaction has become the most intensively studied topic under the title of aquatic pollution in recent years. These studies revealed the bioaccumulation, biomagnification, histological and physiological changes caused by MPs in different organs of different species of fish by standard methods (Banaee *et al.* 2025; Islam *et al.* 2025; Liu *et al.* 2025; de Araujo *et al.* 2025). Investigations

on the biological uptake have revealed that MPs increase the concentration of hazardous compounds in fish organs, which in turn is a health risk to humans by triggering symptoms of endocrine disruption disorder, immune system depletion, and diarrhoea (Yuan *et al.* 2022).

When the studies are analyzed, an important question that remains in mind is whether cultured fish or wild fish is more innocent in terms of MPs. The results of a study on this subject are very interesting, as follows; the MP in aquaculture fugu fish (*Takifugu bimaculatus*) was found to have significantly higher levels (7.91 items per fish) compared to wild, and significant differences were found in MP size and tissue distribution (Song *et al.* 2022). These results show that it is not correct to attribute the threat of MP solely to water pollution, but that it is becoming a problem even in controlled aquaculture environments. In a study, the presence of MP was investigated in different aquaculture stages of cultured trout (sperm, egg, fertilized egg, eyed egg, alevin or such fry, swimming fry and adult trout) and it was determined that while 14 pieces were determined in the periods before feeding, this rate increased by 57% in the feeding stage (Alak *et al.* 2023). The detection of MP presence even in fish in controlled aquaculture environments reveals that the source of MP is not only water pollution. From this point of view, it can be said that feed is also a source of transmission of MP to aquatic environments.

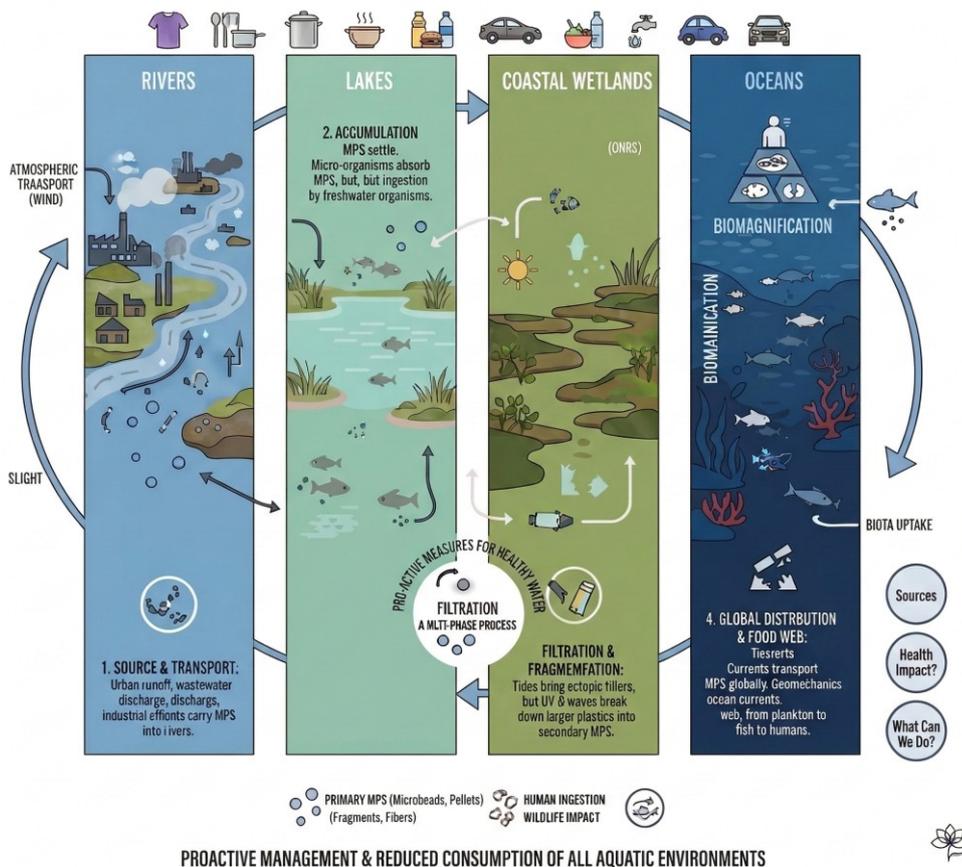
Following the fish, aquatic crustaceans are the most interesting group for MP (Atamanalp *et al.* 2025; Babkiewicz *et al.* 2025; Soegianto *et al.* 2025). The main reason why these groups are more prominent than others is that they play an important role in human consumption. After the MP studies reached a certain stage, research on the health risks that contaminated marine organisms may pose to humans at the consumption level was designed and conducted (Ashry *et al.* 2025; Babkiewicz *et al.* 2025; Jangid *et al.* 2025; Ma *et al.* 2025). The general conclusion from these studies is that, depending on the regions in which they are found, crustaceans may contain MP at levels that pose a risk to humans. The rising prevalence of plastic pollution in marine environments worldwide is a growing concern due to its potential impact on ecosystems and human health (Jamal *et al.* 2025).

When the number and content of studies on MP pollution in higher organisms reached considerable size, aquatic plants and small organisms came to the agenda of those working on this subject. The negative effects of MPs are also inevitable for the plant and micro-components of ecosystems, which were ignored by aquatic toxicologists in the early days because they were postponed and attracted less public attention. The MPs affect almost all the aquatic plants including the aquatic microorganisms, ultimately disturbing the food chain. Aquatic flora attracts MPs due to the formation of several chemical bonds and interactions, including hydrogen

bonds, electrostatic and hydrophobic (Basu *et al.* 2025). Aquatic organisms face substantial risks from MP contamination. However, the influencing factors and mechanisms underlying the toxic effects of MPs remain unclear (Liu *et al.* 2025).

It is now well known that environmental factors influence MP abundance in aquatic organisms. Fish accumulate MPs primarily through feeding, ingesting phyto-

plankton with adsorbed levels of MPs and eating consumers with lower levels of MPs. Eutrophication is an important factor promoting MP bioaccumulation, especially in areas with high MP / phytoplankton ratios (Figure 6) (Liu *et al.* 2025). MPs interaction with aquatic organisms leads to ecological damage in the riverine ecosystem (Kumar *et al.* 2021).



## 2.5 Protection of water resources from MPs

Because MPs are not a very old type of pollution, reduction and control strategies are not yet at the applicable level. Despite studies on strategies to address this issue, very few have been implemented and are considered successful. Since there are so many different ways for MPs to access water resources, humanity is struggling to fill this title. As in all problems faced by living beings, the first step to come to mind in MP pollution is to prevent contamination routes beforehand, which we can define as "preventive medicine" (Figure 2). Since the results obtained in the studies on the retention of MPs in wastewater treatment are not very successful yet, the first precaution to prevent the contamination of water with MP should be taken into consideration. The first thing that comes to mind is reducing the amount of plastic in every product we use in our daily lives. While the wonderful properties of plastics make them indispensable, some countries have begun to implement legal regu-

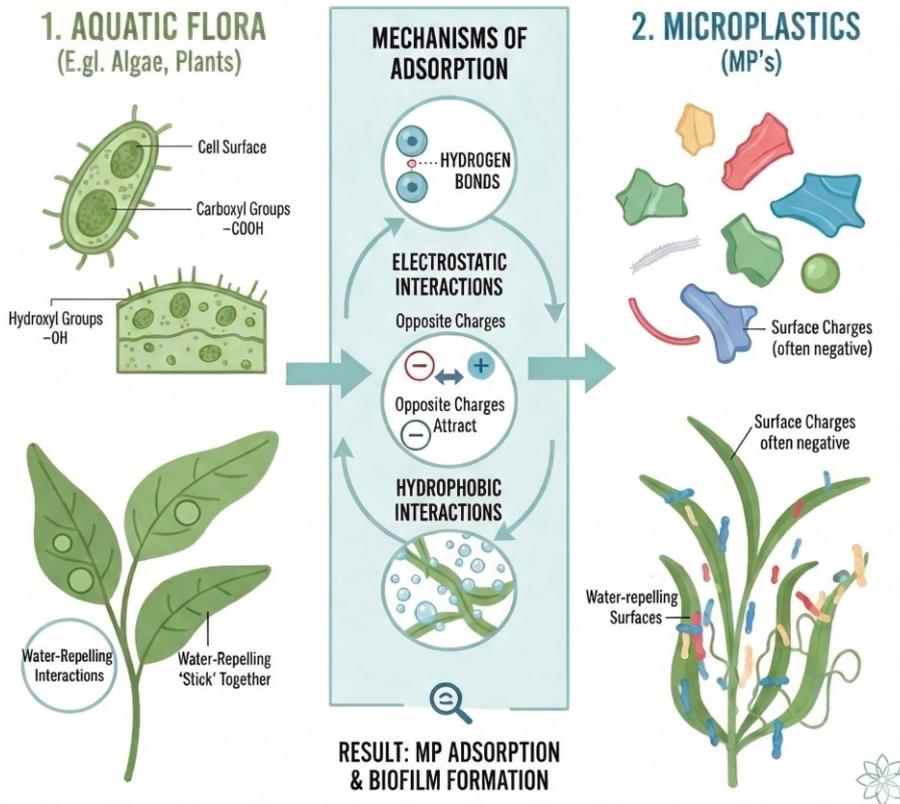
lations on this issue, primarily restrictions on shopping bags and efforts to recycle beverage containers. At this stage, due to official pressure, these bags have been charged, and vending machines that charge a fee for returning the packaging have been introduced in many places. However, the fact that MPs, which are used in large quantities in the manufacture of cosmetics and personal care products, have become an undeniable part of daily life, constitute the most significant source of primary MPs in the environment is still overlooked. A limited number of countries have implemented regulations regarding the manufacturing of these products, directing the use of alternative raw materials.

Strategies to solve the problem of MPs pollution should focus on (i) source control commonly achieved by legislation and awareness programs and (ii) remediation and clean up (to eliminate the MPs already present in water) (Pico and Barcelo 2019).

## AQUATIC FLORA & MICROPLASTICS: CHEMICAL INTERACTIONS

Basu et al., 2025

**FIGURE 6** Aquatic flora vs. microplastic (MP): chemical interactions



International bodies along with national authorities now focus more on MPs as an emerging pollution issue. The development of regulatory frameworks related to MPs remains insufficient in groundwater environments because no specific policies exist (Sumam *et al.* 2025). Another response to microplastic pollution is regulating plastic packaging to reduce waste. Since 60% of plastic waste is generated from packaging, the European Packaging and packaging waste directive (PPWD) of 1994 was reinforced in 2018 with a goal of recycling at least 65% of the weight of all packaging waste by the end of 2025 (Jung *et al.* 2022). As in other sectors, there are significant expectations from nanotechnology-based methods in the removal of MPs from wastewater. In this direction, the research carried out around the world are partially promising. The challenge here is that MPs vary widely in size and origin. The leveling of biobased or biodegradable polymers at the manufacturing stage is an innovative approach to be considered as an important measure to control the presence of MP in waters.

Rivers and lakes, as critical freshwater sources, are being heavily impacted by plastic waste, including microplastics, referring to tiny plastic particles that pose significant risks to aquatic life and water quality. Since water bodies often cross-national borders, pollution in one re-

gion can have widespread consequences downstream, emphasising the need for coordinated international management and regulation in such contexts. Despite the rising awareness of plastic pollution, regulatory frameworks addressing microplastics in freshwater systems remain inadequate and fragmented (Jung *et al.* 2022; Cincurak 2025).

Even if the increase in the production and use of plastics in the world is tried to be stopped, urgent precautionary plans need to be made to dispose of the plastic that has already accumulated in the ecosystem. It is also known that plastic materials turn into micro and nano-sized small plastic particles, causing accumulation and various toxic reactions in terrestrial and aquatic organisms. Even the presence of these micro/nano plastics in human tissues raises concerns. PETase enzyme is thought to be a promising solution to the idea of destroying plastic or converting it into less harmful compounds. By investigating whether this enzyme can be produced by beneficial bacteria or plankton in terrestrial and aquatic environments, these organisms can be used as plastic cleaners in aquatic/terrestrial ecosystems. In addition, by revealing the presence of toxic effects of this enzyme in model organisms and humans, the idea of "whether micro/nano plastics can be destroyed in the digestive sys-

tem and prevented from spreading to other organs by ensuring the production of a beneficial bacteria in the human intestinal system" can be considered. Again, this enzyme can be used in feeds used in fish farming by decapsulation method and by modifying with nanoparticles to maintain enzyme activity. The use of this enzyme in fish feeds brings to mind the idea of "whether it can help to eliminate or reduce MPs in the digestive system, which is the organ where they are most commonly found". There are three most important steps for the implementation of these ideas. The first of these is to determine the toxic effects of this enzyme and to determine safe doses. The second step is to investigate whether different organisms in nature can produce this enzyme. Especially the presence of this enzyme in beneficial bacteria is of great importance. The third step is to find a method (feed, capsule/pill) to administer this enzyme to living organisms without losing its activity. PETase enzymes continue to be researched with great interest in the scientific world. However, since these studies are still in their infancy, more reviews and studies emphasizing the importance of this enzyme should be conducted.

A proposal under the European Chemicals Agency (ECHA) aims to limit major manufacturers from adding MPs into cosmetics products and detergents and fertilizers (Barbosa *et al.* 2019). The efforts of the cosmetics industry have now focused on the identification of sustainable alternatives to non-degradable polymers that are comparable to exfoliating MPs in terms of performance. Three types of biodegradable materials have been proposed as possible substitutes for cosmetics: (a) natural hard materials (e.g., walnut shells), (b) natural polymers (e.g., cellulose and alginate), and (c) biobased and biodegradable synthetic polymers (e.g., poly (lactic acid) (PLA) and polycaprolactone (PCL) (Bikiaris *et al.* 2024).

### 3 | DISCUSSION

The present review highlights the alarming pervasiveness of microplastics (MPs) in aquatic ecosystems, emphasizing their diverse sources, complex behaviors, and far-reaching ecological and human health impacts. The findings from recent studies reveal that MPs are not limited to marine or freshwater habitats but are present across atmospheric, terrestrial, and even biological systems, demonstrating their pervasive and persistent nature (Andrady 2017).

A key outcome observed across multiple investigations is that the bioavailability and toxicity of MPs depend heavily on their size, shape, polymer type, and surface properties. Fibrous and irregularly shaped MPs, due to their high surface area-to-volume ratio, tend to absorb and concentrate toxic organic pollutants and heavy metals more effectively than spherical particles. Ultimately, they pose greater oxidative and inflammatory stress upon

ingestion by aquatic biota (Avio *et al.* 2017). These physicochemical characteristics make MPs powerful vectors for transferring pollutants through trophic levels, amplifying contamination in higher organisms, including humans.

Importantly, the studies examined in this review confirm that aquatic toxicology and food safety are now inseparable disciplines. The widespread detection of MPs in fish, crustaceans, and mollusks—key protein sources for human consumption—demonstrates that MP pollution has transcended from an environmental problem to a public health crisis (Zhao *et al.* 2016; Wright and Kelly 2017). Exposure to MPs through seafood consumption has been associated with endocrine disruption, metabolic alterations, immune suppression, and gastrointestinal inflammation (Browne *et al.* 2011). Furthermore, MPs act as carriers of pathogenic microorganisms and antibiotic-resistant genes, further aggravating ecological and biomedical risks.

From a methodological perspective, the analysis and quantification of MPs continue to present significant challenges. Although advanced spectroscopic and chromatographic techniques such as FTIR, Raman spectroscopy, and pyrolysis–GC/MS have improved polymer identification accuracy, methodological standardization across laboratories remains limited. The absence of universally accepted reference materials and protocols complicates inter-study comparison and undermines global data reliability (Cole *et al.* 2015). Hence, developing harmonized analytical frameworks and implementing international monitoring networks must become research priorities.

Preventive strategies remain the most effective yet underutilized approach. Current evidence indicates that end-of-pipe solutions, such as wastewater treatment and sediment filtration, cannot efficiently remove MPs at micro- or nanoscale levels. Thus, emphasis should shift toward source-oriented prevention, particularly through legislative interventions targeting plastic production, consumer behavior, and product design (Thompson *et al.* 2004; Rochman *et al.* 2015; Shen *et al.* 2019). The transition toward biodegradable polymers and circular economy principles represents a crucial pathway to minimize environmental input. However, the environmental safety and degradation kinetics of bio-based plastics must be critically assessed before large-scale implementation (GESAMP 2016).

Although controlling MP inputs into aquatic ecosystems, which are complex, multifaceted receiving systems, is very difficult, it should not be considered impossible. Recommendations and measures to protect water resources from MP can be grouped under three headings (Sumam *et al.* 2025): (1) banning or restricting MP-containing products; (2) improving wastewater treatment efficiency; and (3) promoting sustainable alternatives.

Finally, interdisciplinary collaboration is essential. Bridging environmental chemistry, materials science, tox-

ecology, and policy research will enable the formulation of comprehensive frameworks for the mitigation of MP pollution (Jambeck *et al.* 2015; Li *et al.* 2018; Hale *et al.* 2020). The concept of “environmental preventive medicine,” as proposed in recent studies (Figure 2), must serve as the guiding principle—prioritizing early intervention, monitoring, and sustainable design to protect water systems and human health alike.

#### 4 | CONCLUSIONS

MP pollution has emerged as one of the most urgent global environmental challenges of the 21st century, posing unprecedented threats to aquatic ecosystems and human well-being. The omnipresence of MPs—from household items and synthetic textiles to automobile components and personal care products—demonstrates that humanity's dependence on plastic has reached unsustainable levels. This review underscores that mitigating the MP crisis requires a multidimensional, systemic approach. Scientific evidence clearly supports that controlling MP pollution must begin at the source, through the reduction of plastic production, substitution with biodegradable materials, and the establishment of extended producer responsibility (EPR) policies. Complementary to this, improvements in waste management infrastructure, especially in developing nations, are vital to prevent leakage of plastic debris into aquatic environments. Research efforts must prioritize:

1. Standardization of analytical methodologies for global comparability and reliability.
2. Comprehensive ecotoxicological studies linking laboratory data with real-world exposure scenarios.
3. Evaluation of biodegradable alternatives, ensuring they do not introduce new ecological burdens.
4. Policy-driven interventions, combining education, legislation, and technological innovation. In conclusion, protecting water resources from MP contamination demands not only technological advancement but also a paradigm shift in production and consumption habits. Recognizing plastics as both a necessity and a threat, humankind must move toward an integrated sustainability model that balances material utility with ecological responsibility. Only through coordinated international efforts can we safeguard aquatic ecosystems—the lifeblood of our planet—from the cumulative toxicity of MPs.

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#### CONFLICT OF INTEREST

The author declares no conflict of interest

#### AUTHORS' CONTRIBUTION

M.A. Searching references, writing D.T. Searching references, writing

#### DATA AVAILABILITY STATEMENT

The data supporting this study's findings are available on request from the corresponding author

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**M Atamanalp**  <http://orcid.org/0000-0002-2038-3921>

**D Türker**  <http://orcid.org/0000-0002-8725-7604>