Molecular & Cellular Toxicology
https://doi.org/10.1007/s13273-022-00289-z

REVIEW

Physical and biomimetic treatment methods to reduce microplastic waste accumulation

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Accepted: 8 September 2022

Abstract

Background Since the Covid-19 pandemic in 2019, the use of plastics has increased exponentially, so it is imperative to manage and dispose of these plastic wastes safely.
Objectives This review focuses on the management strategies governed by the policies of each country to reduce plastic waste through physical collection methods and methods that use eco-imitation technologies.
Results Thus far, physical treatment methods have been applied to sewage and drinking water treatment. The abilities of bio-inspired treatment methods are being assessed in terms of capturing microplastics (MPs) and nanoplastics (NPs), extracting substances from marine organisms, reducing toxicity, and developing alternatives to petroleum-based plastics.
Conclusions Various post-treatment methods have been proposed to collect and remove MPs and NPs that have reached into aquatic ecosystems and subsequently reduce their toxicity. However, there are limitations that the effectiveness of these methods is hindered by the lack of policies governing the entire process of plastic use before the post-treatment.
Purpose of Review We purpose to reduce plastic waste through methods that use eco-imitation technologies.
Recent Findings These eco-imitation methods are attracting attention as viable future plastic waste treatment options in line with the goals of sustainable development.

Keywords Microplastics · Nanoplastics · Biological treatment · Physical treatment · Bio-inspired treatment · Plastic policy

Introduction

As various industries have been using plastics in their processes without appropriate treatments, their excessive usage and low degradability have become critical environmental issues that cause persistent pollution in an ecosystem (Agboola and Benson 2021; Oliveira et al. 2020).

The global use of plastics has grown exponentially over the past few decades. In 1976, 50 million metric tons of plastics were used, which later doubled in 1989. In 2002, the quantity of plastics used doubled again compared to 1989 (Fig. 1). The increase observed in only 10 years indicates a significant upsurge in its usage, which is incomparable to the past (Plastics Europe and EPRO 2021; Statista 2021a). In response to this increase, the governments of several countries, including the United States of America (USA), United Kingdom (UK), and Denmark, implemented a policy to reduce plastic use in the 2010s; however, this has not sustained (Costa et al. 2020; Costa 2021). Due to the outbreak of COVID-19 in 2019, the need for disposable products soared to prevent infection. As a result of the delays caused by the pandemic, the discussions on the regulation of plastics were set back for about 3 years after 2019.

When the COVID-19 pandemic began in March 2020, the collapse of the logistics supply chain caused by the border closures led to a sharp decline in the production by the European plastic industry, but a stronger recovery soon followed (IMF 2020; Plastics Europe and EPRO 2021). In

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Published online: 21 September 2022

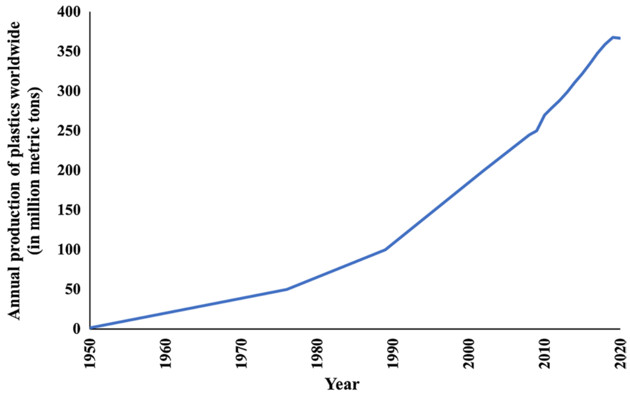

Fig. 1 Annual production of plastics worldwide from 1950 to 2020 (in million metric tons) (Plastics Europe and EPRO 2021; Statista 2021a, b)

response to the pandemic, personal protective equipment made from plastics was widely used, and the generation of disposable plastic medical waste rapidly increased (Klemeš et al. 2020). In addition, some countries, including India and Australia, temporarily delayed the ban on single-use plastics and allowed their use. Therefore, the increase in plastic use during the COVID-19 pandemic is a global phenomenon, and the importance of prioritizing waste management and treatment must be stressed (Yoon et al. 2021).

In 2020, approximately 367 million metric tons of plastics were produced worldwide, with the highest production at 52% in Asia, 19% by the North American Free Trade Agreement, and 15% in Europe (Plastics Europe and EPRO 2021). A 2019 report by the Organization for Economic Cooperation and Development (OECD) shows that 15% of the world's waste plastics were collected for recycling, but only 9% of the recyclable plastics were recycled, and 40% were lost or discarded during recycling. In addition, 46% of waste plastics went to landfills, 17% were incinerated, and 22% were introduced into the environment without being treated by the waste management system (OECD 2022).

Despite the seriousness of plastics flowing into the ecosystem through various routes, their physicochemical properties, health toxicity, ecotoxicity, and bioaccumulation have not been thoroughly discussed. Therefore, further research on the impact of plastic waste on health and ecosystems is required.

Microplastics (MPs) and Nanoplastics (NPs) flow into rivers through point pollution and non-point pollution sources. Before plastics enter the ecosystem, they need to be filtered and removed; however, the technology for this process is not yet available. Therefore, this research reviewed the following topics: types and properties of plastics, the after-use condition of MPs and NPs that persist in the environment, the chemical affinity of plastics due to their chemical properties, and bioaccumulation. Most importantly, this study analyzes three key concepts: the viable options to manage incidents, where plastics have already entered the environment, the application of bio-inspired technology, and the governmental policies to reduce the generation of plastics through life cycle management (Fig. 2).

Plastic types and characteristics

Plastics are used in various industries, with the packaging industry (40.5%) using the most in the EU in 2020, followed by the building and construction (20.4%), automotive (8.8%), and electrical and electronics (6.2%) industries (Fig. 3a. The most common plastic material produced in the EU was polyethylene (PE) at 30.35%, of which low-density polyethylene (LDPE) and linear low-density polyethylene accounted for 17.45% and medium-density and high-density polyethylene (HDPE) at 12.9%. The demand was high for polypropylene (PP) at 19.7%, polyvinyl chloride (PVC) at 9.6%, polyethylene terephthalate (PET) at 8.4%, and polystyrene (PS) at 6.1% (Fig. 3b Plastics Europe and EPRO 2021). PE was also produced the most in the USA, followed by PP and PVC (Statista 2021b).

Plastics are divided into thermosets and thermoplastics according to their properties when heated. Thermosets are rigid and stable, but cannot be reprocessed by softening and molding. On the other hand, thermoplastics are relatively easy to recycle as they can be molded at high temperatures and have an elastic or solid shape at room temperature (Agboola and Benson 2021; Oliveira et al. 2020). The types and characteristics of major plastics are shown in Table 1.

PE has a variety of uses in film, packaging, and electrical insulation to container piping. It can be classified as an LDPE or HDPE due to the differences in resistance, toughness, flexibility, and clarity to chemicals (Oliveira et al. 2020). An LDPE is a solid and flexible polymer characterized by long branches, and an HDPE can be packaged closer to crystallites as polymer chains become more linear (Jordan et al. 2016). PVC, which is the most commonly used plastic resin in medical devices, is chemically non-reactive, rigid, and easily welded and thermoformed (McKeen 2014). PS is thermally stable, has high translucency and durability, and is a thermoplastic polymer that can be easily dyed. These characteristics make PS suitable for food storage and transportation and producing packaged products and toys (Kik et al. 2020). PP is a thermoplastic material manufactured by polymerizing propylene molecules in monomer units into long polymer molecules or chains (Shubhra et al. 2013; Willam et al. 2003). PP is lighter in weight than PS due to its lower specific gravity. Furthermore, PP has high rigidity and impact resistance. PP is used in slit films, carpets, cast films, and rigid

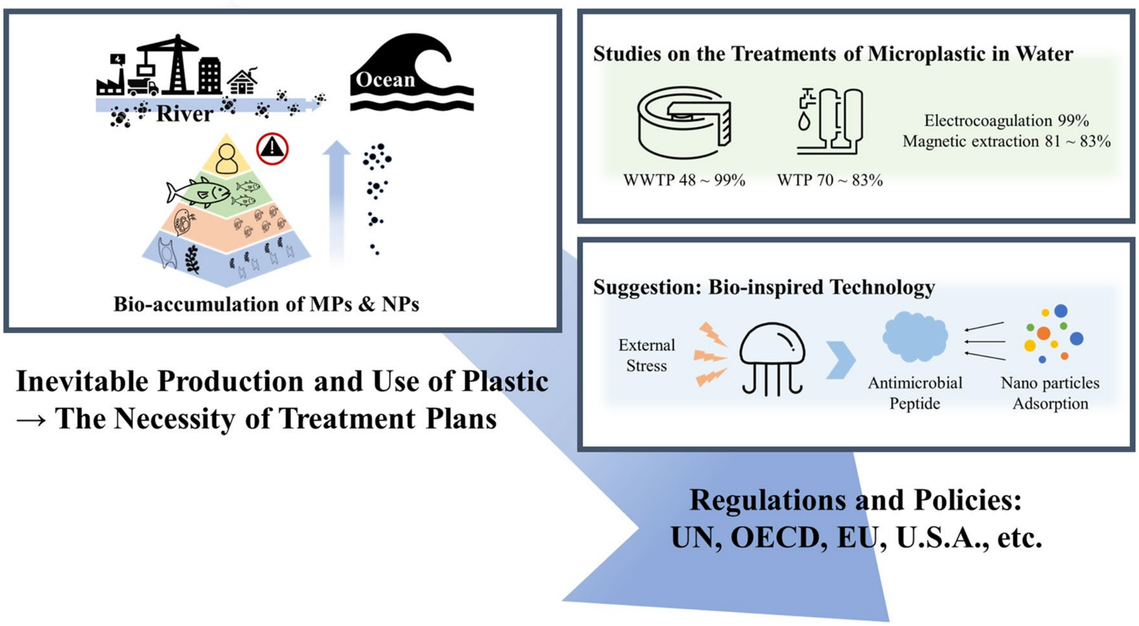

Fig. 2 Research topics of microplastic

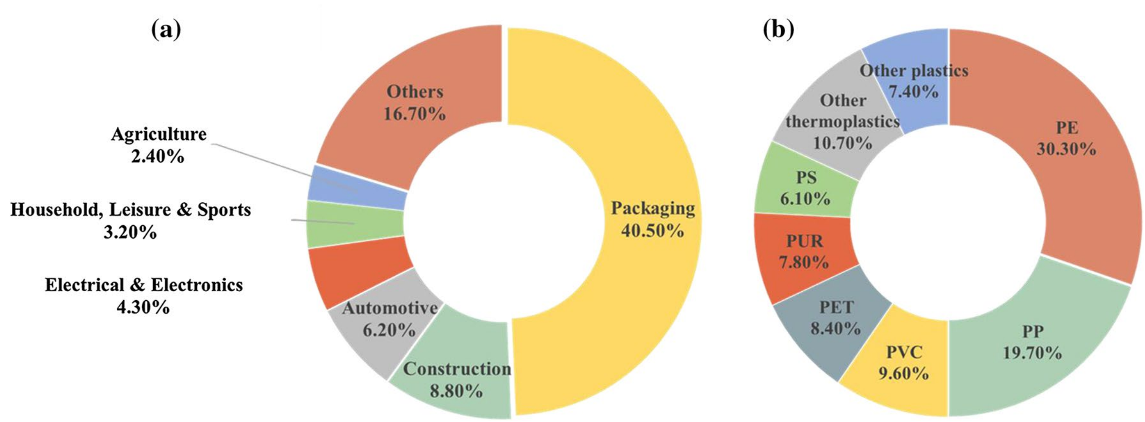

Fig. 3 **A** Plastics demand in the EU in 2020. **B** Plastic resin types in the EU in 2020 (based on Plastics Europe 2021)

packaging containers (Willam et al. 2003). PET has low friction and high wear resistance and is resistant to dilute acid, aliphatic and aromatic hydrocarbons, and water at room temperature. It appears white in a semi-crystalline state and transparent in an amorphous state. Amorphous PET has a relatively lower hardness, rigidity, and thermal resistance than crystalline PET (Ji 2013).

The secondary pollution problem caused by plastics

Plastic debris persist in the environment and can become nano-sized; therefore, it is necessary to evaluate the toxicity of plastics according to the size of plastic fragments.

Plastic fragments can be classified into: macroplastics (> 25 mm), mesoplastics (5–25 mm), MPs (< 5 mm), and NPs (< 100 nm) (Fig. 4). In general, MPs are defined as less than 5 mm, with the European Chemical Agency, the National Oceanic and Atmospheric Administration, and the European Food Safety Authority following the same

Table 1 Plastic types and characteristics

Plastics/chemical structure	Characteristics	Uses	References
Polyethylene (PE)/$(C_2H_4)_n$	- Characterized based on density and the degree of molecule branching - Semi-crystalline - Processability - linear chain	Packaging, textiles, piping	Jordan et al. (2016), Oliveira et al. (2020)
High-density Polyethylene (HDPE)/ $(C_2H_4)_n$	- Large density to strength ratio - Heat resistance/heat stable	Milk packaging, shampoo containers, pipe	Jordan et al. (2016), Oliveira et al. (2020)
Low-density Polyethylene (LDPE)/ $(C_2H_4)_n$	- Tough and flexible polymer - Resistant to acids, alcohols, bases, esters -Long branches - Transparent - Hard to recycle	Packaging films, shopping bags	Jordan et al. (2016), Oliveira et al. (2020)
Polyvinyl chloride (PVC)/$(C_2H_3Cl)_n$	- Thermoplastics and non-crystalline - Good clarity and transparency retention - Sensitive to UV - Good chemical resistance and stability - Chemically nonreactive	wrapping, sheets, window frame, pipe, bumpers, medical devices	McKeen (2014)
Polystyrene (PS)/$(C_8H_8)_n$	- High translucency - High durability - Thermally stable - Easy to dye	Toothbrushes, CDs, Styrofoam	Kik et al. (2020)
Polypropylene (PP)/$(C_3H_6)_n$	- Light weight - Dimensional stability - High impact resistance - Transparency - Flame resistance - Chemical and stain resistance	Slit film, carpets, cast film, sheet, rigid packaging containers, caps and closures, disposable syringes	Shubhra et al. (2013), Willam et al. (2003)
Polyethylene terephthalate (PET)/ $(C_{10}H_8O_4)_n$	- White in semi-crystalline - Transparent in amorphous state - Not resistance to alkalis, esters, etc. - Resistant to dilute acids, fats, etc. - Resistance to water at room temperature - Low friction and high abrasion resistance - High hardness	Water bottles	(Ji 2013)

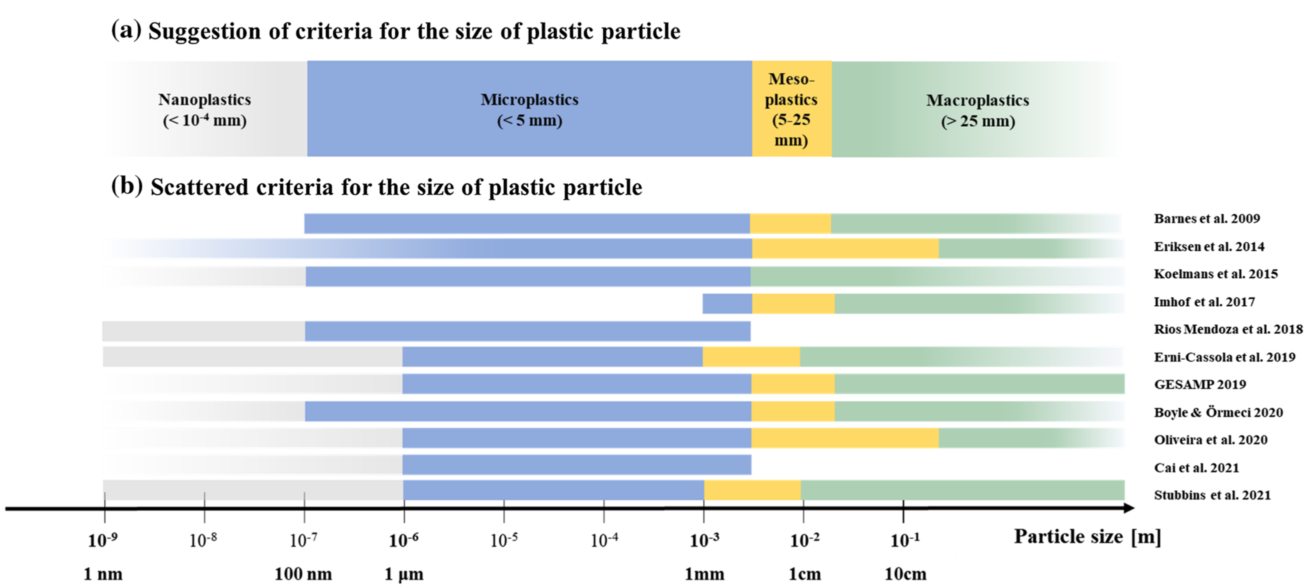

Fig. 4 Criteria for the size of plastic particles. **a** Suggested criteria for the size of plastic particles, **b** scattered criteria for the size of plastic particles. (Barnes et al. 2009; Boyle and Örmeci 2020; Cai et al. 2021; Eriksen et al. 2014; Erni-Cassola et al. 2019; GESAMP 2019; Imhof et al. 2017; Koelmans et al. 2015; Mendoza et al. 2018; Oliveira et al. 2020; Stubbins et al. 2021)

standard (Anagnosti et al. 2021; EFSA Panel on Contaminants in the Food Chain (CONTAM), 2016). However, NPs are not clearly defined, because several studies classify plastics with sizes less than 1 μm as NPs (Andrady 2017; Imhof et al. 2017; Ramasamy and Palanisamy 2021). Therefore, we suggest some criteria to resolve the uncertainty in the size of plastic particles (Fig. 4).

There are two types of MPs: primary MPs and secondary MPs. Primary MPs are produced during the manufacturing stage in sizes that are less than 5 mm and are used in cosmetics and sanity products (Andrady 2011; Ha and Yeo 2018; Thompson 2015). Secondary MPs are introduced into the environment mainly through general waste, improper management of landfills, loss during collection, and wear of tires and paint (Boyle and Örmeci 2020; Duis and Coors 2016).

Most of the plastic waste found in the ocean comes from land-based plastics (Andrady 2011). MPs, in particular, are ubiquitous in the oceans, including polar regions (Barnes et al. 2009; Zarfl and Matthies 2010). Accumulation of plastics in the environment negatively affects living organisms. The introduction and accumulation of plastics in the environment is known as primary pollution. However, secondary pollution refers to the introduction and accumulation of the plastics combined with hydrophobic substances, such as persistent organic pollutants (POPs) into the body of living organisms.

Synthetic organic polymeric plastics made by refining petroleum or gas are polymeric materials (Sánchez 2020) that remain in the ocean for a long time because of their difficulty in decomposing when in their natural state (Hopewell et al. 2009). The decomposition of plastics involves non-biological decomposition that occurs by various physical and chemical processes and biological decomposition that occurs through microorganisms (Oliveira et al. 2020).

Non-biological decomposition of plastics is carried out through chemical processes, such as photolysis, thermal oxidation and pyrolysis, structural cracking, reduction of ductility, physical or oxidation, and bond cutting (Chen et al. 2018; Li et al. 2004). The photolysis of plastics is caused by UV-C wavelengths in the sun's ultraviolet rays. When exposed to ultraviolet rays under oxygenated conditions, photooxidation occurs, and through this process, the chains of plastic polymers are decomposed, and physicochemical properties and surface shapes are changed (Andrady 2011; Lin et al. 2020; Martínez et al. 2004). A thermal oxidation reaction refers to the decomposition of polymer chains by the action of light and heat under oxygenated conditions (Drozdov 2007; Oliveira et al. 2020). In pyrolysis, plastics are decomposed, because high temperatures reduce the stability of polymer structures, causing chemical changes (Kamo et al. 2004).

The biodegradation of plastics occurs mainly by bacteria, fungi, and enzymes, and it is affected by the properties of plastics and the environmental factors (Bardají et al. 2020; Sánchez 2020). Microorganisms that break down plastics have different population distributions depending on the environmental conditions in soils and oceans; therefore, the decomposition of plastics by microorganisms is affected by the surrounding environment.

An important step in biological decomposition is the attachment of microorganisms to the plastic surface to form a colony; this is affected by the surface conditions and structures of the plastic. When the enzyme binds to the plastic surface, it is hydrolyzed from low molecular oligomers to dimers and monomers using polymers as a substrate and is then finally decomposed into CO_2 and H_2O (Oliveira et al. 2020; Tokiwa et al. 2009). Therefore, the degree of biological decomposition may vary depending on the surface conditions of plastics, i.e., the surface area, hydrophilicity, and hydrophobic properties. The effects can vary depending on the chemical structure and molecular weight of the plastic, the degree of biological degradation due to glass transition temperatures, crystallinity, and the crystal structure of plastics (Tokiwa et al. 2009).

It is considered that the affinity of plastics to other chemicals and their ecosystem accumulation is influenced by not only the chemical properties but also the physicochemical structure of the plastic material. The NPs of PS generally have carboxyl (-COOH) and amine ($-NH_2$) functional groups, which result in surface charge and reactivity (Zhang et al. 2019). In addition, oxygen-rich functional groups are produced during photolysis, and the reactivity subsequently increases (Andrady 2011). To commercialize plastics, depending on the purpose of the processing, additives such as plasticizers, flame retardants, stabilizers, antioxidants, heat stabilizers, and brominated flame retardants are added (Hahladakis et al. 2018). These additives are endocrine disruptors that cause hormonal abnormalities when introduced into the body and are likely to leach into the environment during the decomposition of plastics (Endo et al. 2013; Hermabessiere et al. 2017).

Plastics enter the marine environment through many channels (Enders et al. 2015), and those that have been introduced and broken into smaller pieces have a higher affinity to hydrophobic molecules than water (Rios et al. 2010). Consequently, marine plastics combine endosulfan, a hydrophobic substance that has been released in the ocean, and dichloro-diphenyl-trichloroethane, polychlorinated biphenyl, polycyclic aromatic hydrocarbons such as POPs combine with carry these substances (Lee et al. 2014; Rios et al. 2007).

MPs are present at the ocean's surface and in the depths and are likely to be consumed by various marine organisms (Betts 2008). Invertebrates consume MPs, because they are partially indistinguishable from planktons due to their similar sizes (Browne et al. 2008; Graham and Thompson 2009).

In addition, not only zooplankton at the bottom of the food chain consume MPs but also other marine animals, such as fish, shellfish, and crustaceans (Eom et al. 2020). There is much concern about human health due to the accumulation of plastics through bioenrichment (Cauwenberghe and Janssen 2014; Cole et al. 2011; Murray and Cowie 2011).

Concerns have been raised about the potential toxicities of MPs and NPs as chemical carriers in living organisms. This means that MPs and NPs absorbed into the body from the digestive system can be transported to various organs in the body, causing toxicity at the cellular and molecular level (Kim and Rhee 2021; Shen et al. 2019). Plastics accumulated in the liver can result in oxidative stress through inflammation and lipid accumulation (Lu et al. 2016). PS nanoparticles can penetrate and bind to the lipid membrane, changing its structure and properties and affecting cell function (Rossi et al. 2014). POPs and heavy metals in the environment are adsorbed to the surface of the plastics due to the hydrophobic properties that occur when plastics are decomposed. Therefore, the smaller the size of the plastic, the higher the risks are of being transferred into organs, tissues, and cells and becoming concentrated and inducing toxicity (Lee et al. 2019; Salvati et al. 2011; Teuten et al. 2007; Velzeboer et al. 2014).

Potential toxicity of plastics

Among plastics, many studies on the potential toxicity of PS have been conducted. PS MPs, when exposed to zebrafish larvae, affect their intestinal metabolites and are involved in energy metabolism of glutamine, sarcosine, pyruvate, and creatine (Wan et al. 2019). Zebrafish chorions have pores with diameter 0.5–0.7 µm for the movement of oxygen and nutrients, where NPs can be introduced. Particles larger than the pore size attach to the chorion and are introduced into the interior by the flow of water. Plastic accumulates in the mouth, gills, brain, blood vessels, liver, heart, intestines, and muscles of larvae and adult zebrafish (Bhagat et al. 2020). In zebrafish embryo, after 48 h of 50 nm PS exposure, fluorescence imaging results showed the accumulation of various types of tissue and cells, including lipid-rich regions, nerve systems, yolk, and muscle fibers, as well as NPs penetrating the chorion. Although mortality and phenotypic abnormalities due to PS NPs were not high, they increased the toxicity caused by other substances, such as metal ions (Lee et al. 2019). In addition, the toxic effects varied depending upon the size. Although PS with 10–100 µm diameter was not significantly cytotoxic, smaller PS with 460 nm and 1 µm diameter affected red blood cells (Hwang et al. 2020). 50 nm PS accumulates in the head of zebrafish embryos, resulting in decreased exercise and swimming ability, and seizures. This suggests that NPs can pass through the blood–brain barrier (Bhagat et al. 2020).

Material properties of MPs, such as density, crystallinity, biodegradability, oxidation, additives, and surface properties affect ecosystem behavior, causing them to act as carriers of contaminants, such as heavy metals and polycyclic aromatic hydrocarbons (Andrady 2017; Wang et al. 2021).

NPs have unique physicochemical properties; therefore, their behavior is difficult to predict, and can have various effects on humans and the environment (Klaine et al. 2012; Mitrano et al. 2021). The density of NP aggregates varies according to the polymer shape, surface area, degree of contamination of the organic material, and thickness. A large surface area causes strong adsorption of external harmful chemicals and carries hydrophobic materials and trace metals (Koelmans et al. 2015).

The effect of different polymer types of MP, including PE, PP, and PVC on the adsorption, accumulation and toxic effects of triclosan(TCS) in zebrafish was evaluated. All three types of MP were capable of adsorption of triclosan and had an effect on metabolic disorders. Among them, TCS + PP showed the highest adsorption capacity, disrupted liver metabolism, and enhanced brain neurotoxicity. In addition, the accumulation of TCS in the liver and intestine of zebrafish increased in the order of TCS + PP, TCS + PVC, and TCS + PE, respectively (Sheng et al. 2021).

Solutions under consideration: (1) Physical treatment methods

MPs are recognized as a serious environmental problem due to their particle characteristics and toxicity. The steps to solve for MP contamination include: (1) post-treatment for the physical collection of MPs that have already been discharged, (2) utilization of bio-inspired technology, and (3) reduction of plastic emissions during the production, use, and disposal of plastics.

MPs are often used in consumer products, such as personal hygiene products and laundry detergents (Andrady 2011), which can be introduced into the aquatic ecosystem through sewage treatment and wastewater treatment plants (WWTPs) (Carr et al. 2016). When using a membrane bioreactor among tertiary treatments in existing WWTPs (Table 2), it achieved a 99.9% reduction in MPs with a size of > 20 µm. Furthermore, micro-filtration using a 20 µm disc filter lead to a 98.5% reduction in MPs (Talvitie et al. 2017). MPs in drinking water are a cause for concern, particularly for human health, but the MP reduction ability of water treatment plants (WTPs) (Table 3) is promising, with reductions of up to 70–83% (Pivokonsky et al. 2018).

NPs with particle sizes of less than 100 nm are rarely treated in WWTP and WTP processes and are discharged into

Table 2 Plastic removal efficiency in water treatment

Treatment Stage	Significant treatment technology	Removal efficiency (%)	Plastic size (> µm)	References
Tertiary treatments				
	Micro-screen filtration with disc filter (20 µm)	98.5 (concentration)	20	Talvitie et al. (2017)
	Rapid sand filter	97.1	20	
	Dissolved air bioreactor	95.0	20	
	Membrane bioreactor	99.9	20	
	Biological and chemical phosphorus removal units	48	500	Akarsu et al. (2020)
Secondary treatment				
	Screening (mesh size: 6 mm), primary sediment, aeration, and final sediment	73	500	Akarsu et al. (2020)
	Screening (mesh size: 6 mm), primary sediment, aeration, and final sediment	60	500	

Table 3 Plastics removal efficiency in water treatment plants

Treatment technology	Removal efficiency (%)	Plastic size (> µm)	References
Coagulation/flocculation, sand filtration	70	0.2	Pivokonsky et al. (2018)
Coagulation/flocculation. Sedimentation, granular activated carbon filtration	81	0.2	
Coagulation–flocculation, flotation, sand filtration, granular activated carbon filtration	83	0.2	

lakes and rivers or remain in sludge (Boyle and Örmeci 2020). Therefore, despite the high reduction rates of plastic particles in wastewater, the amount of plastics discharged into the environment is still high, suggesting that a treatment method targeting only MPs and NPs is required.

Perren et al. (2018) studied the efficiency of electrocoagulation (EC) for MP removal from wastewater. EC is a process, whereby magnetic fine powder is added to wastewater containing suspended solids and stirred to generate flocs. These flocs are then attached to a magnetic mattress and removed (Kim et al. 2014). EC shows promise for building an automated system, because it does not depend on chemicals or microorganisms, is cheap, and generates little waste. In this study, EC based on fine $Al(OH)_3$ showed that the optimal removal efficiency of PE microbeads with a particle size of 300–355 µm was 99% at pH 7.5.

Grbic et al. (2019) studied magnetic extraction as a method for separating MPs from environmental samples. The addition of iron nanoparticles to hexadecyltrimethoxysilane solutions causes hydrophobization of iron particles. It promotes the hydrophobic interaction of iron ions with MPs, thereby allowing the iron ions to adhere to MPs.

Solutions under consideration: (2) Application of bio-inspired technology

Nature has been trained through evolution to achieve effective and efficient mechanisms for survival in harsh environments for billions of years, and humans have always drawn inspiration from this for use in everyday life. Technology learned from nature is referred to as “biomimetics” (Bar-Cohen 2006).

MPs, the most important environmental pollutants recently, accumulate in large amounts in water and adversely affect human health (Smith et al. 2018). Therefore, it is important to know if biomimetics can be applied to eliminate MPs in water environments and prevent their harmful effects on human health.

There have been many reports of frequent mass emergence of jellyfish due to eutrophication by human activities and sea temperature increases due to climate change (Behera et al. 2020; Boero 2013; Kim et al. 2012; Purcell et al. 2013). Outbreaks of jellyfish can not only destroy the marine ecosystem but also cause damage to the marine fishing industry by clogging fishing nets and boat gears. Large jellyfish populations can also destroy aquaculture by killing fish in cages and destroying power plants by blocking the seawater-cooling intake. They also negatively affect local tourism by stinging swimmers. These negative impacts of jellyfish blooms result in local economic loss; thus, the occurrence of jellyfish is unfavored by the coastal residents. For example, a study conducted in Korea reported that the fishery catch had decreased by 33% due to the mass emergence of jellyfish (Kim et al. 2012). Hence, jellyfish outbreaks have been recognized as a nuisance to the coastal residents.

Cnidaria phylum, including *Hydra* and jellyfish, possess an innate immune system and secrete antimicrobial peptides under external stresses (Bakshani et al. 2018; Lee et al. 2020). When Cnidaria are exposed to environmental changes or are in direct contact with other organisms, they activate their immune system and release mucous. The mucus obtained from a species of jellyfish, *Aurelia aurita*, has been proven to bind with NPs and reduce its toxicity (Geum and Yeo 2022; Ha et al. 2020; Kim et al. 2022; Patwa et al. 2015). Geum and Yeo (2022) demonstrated that over 90% of the polystyle-NPs ($2.0\ mg \times L^{-1}$) were captured within 30 min by $100\ \mu g \times L^{-1}$ mucin of *A. aurita* and the toxicity of the NPs on zebrafish hatching rate also decreased. Therefore, the use of jellyfish can be applied as a method for eliminating MPs in water and removing jellyfish blooms from coastal areas.

Jellyfish can be easily caught with fishing nets during bloom. When physical stress is applied using a simple tool, the mucus secreted by jellyfish can be used to remove MPs (Geum and Yeo 2022; Ha et al. 2020; Kim et al. 2022). After the mucus secretion, jellyfish undergo a natural process of apoptosis and decompose in water (Tinta et al. 2021). While jellyfish are processed to remove MPs, no harmful chemicals are added, and no action is required which emits greenhouse gases or accelerates climate change, such as using fossil fuels. In other words, the application of jellyfish for MP reduction in water can be described as one of the most strongly demanded sustainable low-carbon environmental technologies in the world today (Yuan et al. 2011).

However, there are limitations to using jellyfish in reducing plastic pollution; since jellyfish blooms only appear during certain seasons, it is impossible to catch jellyfish in their natural state continuously. Since the demand for edible jellyfish has increased, there has been ongoing development of jellyfish aquaculture technology in China since the 1980s, and there were reports of a successful culture of jellyfish in the 2000s (You et al. 2007). Therefore, it may be possible to obtain jellyfish year-round through jellyfish aquaculture. Another way to continuously supply jellyfish mucus is through a biochemical method that specifically analyzes the components of the mucus and artificially synthesizes it. However, jellyfish aquaculture and mucus synthesis are not economically viable. Nevertheless, the reduction of MPs with jellyfish mucus is worth considering.

The United Nations Environment Assembly (UNEA) and the OECD emphasize the importance of managing plastic pollution throughout the life cycle of plastics (OECD 2021; UNEP 2022). This means that not only is it important to reduce the amount of plastic waste itself by reusing, recycling, and remanufacturing the used plastics, but it also means that efforts should be made to minimize the amounts of plastics that are indirectly released into the environment, such as when MPs are released during the washing of clothes. In other words, the technology to remove MPs during the treatment process in WWTPs or when discharging domestic wastewater must be considered. This is the point, where bio-inspired jellyfish technology can be applied easily. Therefore, the removal of MPs using jellyfish is proposed as an eco-friendly and biomimetic technology for reducing plastic pollution.

The technique of MP removal using bio-inspired technology is also proposed when considering the gills of marine fish. Fish obtain feed through a unique non-logging solid–liquid filtration mechanism called ricochet separation. In this way, planktons smaller than the slits between gill rakers are filtered into the fish and then ingested. This bio-inspired technology of the filtration system of marine fish has been reported to effectively remove 97.6% of MPs of 700 nm size (Zhang et al. 2022).

The caddisfly *Odontocerum albicorne* (Scopoli 1763), also found in freshwater, has been known to make diagnostic cases out of sand and gravel. However, when exposed to plastics, *O. albicorne* interacted with MPs rather than natural construction materials and substrates to make its cases. Research showed that this type of fish interacted with almost any type of MPs (acrylonitrile butadiene styrene, PET, PP, PS, and polyvinylidene fluoride) (Gallitelli et al. 2021). The caddisfly larvae gather MPs and construct diagnostic cases, and consequently, the MPs are removed. However, the stress in the ecological cycle of caddisfly larva caused by MPs has not yet been investigated; therefore, further research is needed.

The effect of intestinal microorganisms on MPs decomposition has been thoroughly studied. *Tenebrio molitor* larvae are particularly known to have conspicuous abilities to decompose organic matter. Przemieniecki et al. (2020) reported that after these microorganisms consumed PS and PE for 70 days and decomposed 12.2% of PS and 16.6% of PE. It is presumed that the decomposition is due to the action of intestinal microorganisms in *T. molitor* larvae. Microbial cluster analysis at the genus level confirmed that it accounted for a high proportion in the order of Proteobacteria > Bacteroidetes > Firmicutes > Actinobacteria (Przemieniecki et al. 2020).

The natural resources that can replace MPs originating from petroleum plastics are currently of interest. Cellulose nanofiber (CNF), derived from plants or produced by bacteria, is one of the most common natural ingredients. As an alternative plastic manufacturing method, "directional deforming assembly," inspired by CNF, was proposed. CNF was used as a high-performance one-dimensional nanoscale building block because of its high strength, low coefficient of thermal expansion, and abundant hydroxyl and carboxyl groups on the surface. The mica microplatelet (exfoliated from natural mica and coated with TiO_2) was used as a natural two-dimensional block (Guan et al. 2020). This bio-inspired structural material may be an alternative material for existing plastics because of its superior mechanical and thermal properties compared to petroleum-based plastics.

As such, bio-inspired technology research is actively underway as a solution to environmental problems caused by plastics in various processes, such as material, treatment, collection, and removal. It is also attracting attention as a viable option, because it fits the goal of developing future eco-friendly technologies for sustainable development.

Restriction and policies on production, use, and disposal of plastics

In March 2022, the fifth session of the UNEA held in Nairobi adopted 14 resolutions, including one to "End plastic pollution." To end plastic pollution, the world's environmental ministers agreed to establish an intergovernmental negotiating committee with an international legally binding agreement by 2024 (UNEP 2022). The resolution addresses the plastic pollution problem and deems it necessary to be dealt with across national borders as well as throughout the production, design, and disposal of plastics (UNEP 2022).

Recently, the OECD reported that recent restrictions on single-use plastics and microbeads in rinse-off cosmetics might reduce some plastic use and entry into the environment. Simultaneously, they criticized that MPs released from the wear and tear of products, which account for a substantial part of the release, are not considered in current policy frameworks. The OECD recommended that prevention of MP release during the manufacturing step of plastic products has the largest reduction potential and is the most cost-effective way to mitigate MPs in the environment. Nevertheless, MPs released at different points during the life cycle of plastics should also be considered (OECD 2021).

There are currently no comprehensive regulations in the EU law applicable to MPs, and there are also no economic incentives to encourage businesses to reduce their emission of MPs. However, in February 2022, the European Commission (EC) launched a public consultation on reducing the amount of "unintentionally released MPs" into the environment. The consultation focuses on sources that release the largest quantity of MPs, such as plastic pellets, synthetic textiles, and tires (EC 2022). In the case of "intentionally added MPs," the European Chemical Agency (ECHA) proposed a restriction after assessing the risk reduction potential and socio-economic impacts. The restriction of MPs is comprised of three types of measures: (i) a restriction on placement on the market, (ii) a labeling requirement to minimize releases to the environment, and (iii) a reporting requirement to improve the quality of information. Particularly, MPs on their own or in mixtures, where their use will inevitably result in releases to the environment are restricted from being placed on the market, but a transitional period will be available to allow sufficient time for stakeholders to comply with the restriction (ECHA 2019).

In 2021, the EU banned the sale of single-use plastic products, such as cotton bud sticks, cutlery, and straws, which are commonly littered on the European beaches, and by 2030, all plastic packaging placed on the EU market will be reusable or easily recyclable to improve the economics and quality of plastic recycling (EC 2018). Countries such as France, Italy, Sweden, the United Kingdom, Netherlands, and Spain have introduced legislation to restrict MPs intentionally added to products during the manufacturing process (Park et al. 2019).

In the USA, Congress passed the new law, Microbead-Free Waters Act of 2015, prohibiting the manufacturing, packaging, and distribution of rinse-off cosmetics containing intentionally added plastic microbeads. Under this law, the manufacturing, introduction, and delivery of all types of rinse-off cosmetics have been restricted since 2019. This law applies to both cosmetics and non-prescription drugs, such as toothpaste (United States Congress 2015). Canada has enacted the "Microbeads in Toiletries Regulation'" to ban the manufacture, import, and sale of toiletries containing plastic microbeads under 5 mm (Canada 2017).

In the Korean safety standards for cosmetics, MPs were put on the list of products that cannot be used in cosmetics, and thus, the manufacture, import, and sale of Quasi-drugs using solid plastics smaller than 5 mm were prohibited (Korea 2015).

Individual countries, including France (2016), the UK (2017), New Zealand (2017), and Korea (2018), have already adopted policies to restrict the use of single-use plastics to reduce the production of plastic wastes and to increase the recycling rate of plastics (France 2016; Korea 2018; New Zealand 2017; UK 2017). France was the first county in the world to adopt a law stating that by 2025 every new washing machine must be equipped with a filter for capturing MPs released from clothes during washing (Frédérique 2020). In addition, the global electronics manufacturer, Samsung Electronics, announced at the CES 2022 that they would develop a washing machine that can filter out MPs and prohibit them from being released into the environment (David and Ian 2022).

So far, regulatory policies have been made mainly for MPs intentionally added during the manufacturing and distribution stages, but regulation of the disposal stage is also necessary.

To effectively implement a variety of policies aimed at reducing MPs, it is essential to evaluate and monitor the actual risk of MPs in the environment. However, since MPs vary in their characteristics, such as size, shape, color, and chemical composition, no standardized protocol for accurate sampling, extraction, purification, and qualitative and quantitative analysis of MPs has clearly been established yet (Hidalgo-Ruz et al. 2012; Silva et al. 2018).

The cheapest and easiest way to quantify MPs is via visual assessment, but the data will vary depending on the examiner, and MPs can be incorrectly identified as organic particles or vice versa, which is relatively inaccurate. Since Fourier transform infrared spectroscopy (FTIR) detects the structure and weathering degree of MPs, it has the advantage of determining the source and entry route of MPs. However, FTIR cannot detect dark or opaque MPs, and it is time-consuming as it analyzes particles one by one. The thermodynamic analysis also has the disadvantage of taking a long time to process the sample, and if a similar decomposition product is generated, wrong results may be obtained. Therefore, to obtain reliable monitoring data, it is necessary to establish an improved and unified methodology that efficiently analyzes MP types and components (Gong and Xie 2020; Lanctôt et al. 2018).

Conclusions

Since the COVID-19 pandemic, the use of plastics has increased exponentially as a way to prevent the spread of infection. MPs and NPs leached into the ecosystem are carriers of toxic substances and affect ecosystem organisms as well as humans. The fragments of MPs and NPs act as carriers of highly persistent toxic substances that should be addressed.

Physicochemical treatment and biological treatment methods are being considered as a tool to capture and remove MPs and NPs released into the aquatic ecosystem and to reduce their toxicity. In addition, bio-inspired treatment methods for collecting and removing MPs and NPs represent eco-friendly technologies that do not cause secondary pollution. These can effectively reduce the MPs and NPs that have been released into the ecosystem.

Acknowledgements This work was supported by the Korea Environment Industry and Technology Institute (KEITI), through the Ecological Imitation-based Environmental Pollution Management Technology Development Project, funded by the Korean Ministry of Environment (MOE) (2021002800019).

Author contributions MKY: conceptualization (equal); funding acquisition (equal); Supervision (equal); writing—review and editing (equal). HL: writing—original manuscript, reviewing and editing (equal); data curation (equal). JES: writing—original manuscript, reviewing and editing (equal); data curation (equal). IHP: writing—original manuscript, reviewing and editing (equal); data curation (equal). KSC: writing—original manuscript, reviewing and editing (equal).

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflicts of interest The authors declare that they have no competing interest. Hyesoo Lee declares that she has no conflict of interest. Joo Eun Shim declares that she has no conflict of interest. In Hae Park declares that he has no conflict of interest. Kyung Sil Choo declares that she has no conflict of interest. Min-Kyeong Yeo declares that she has no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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