Science of the Total Environment 892 (2023) 164531

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Review

Polystyrene microplastic particles in the food chain: Characteristics and toxicity - A review

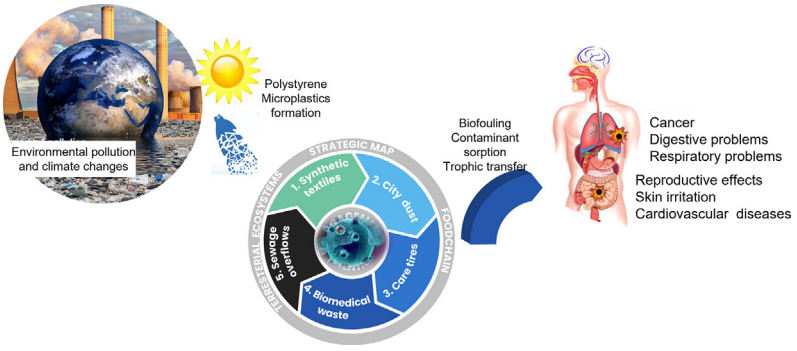
Shahida Anusha Siddiqui [a,b,*], Shubhra Singh [c], Nur Alim Bahmid [d,e], Douglas J.H. Shyu [f], Rubén Domínguez [g], Jose M. Lorenzo [g,h], Jorge A.M. Pereira [i], José S. Câmara [i,j,**]

[a] Technical University of Munich Campus Straubing for Biotechnology and Sustainability, Essigberg 3, 94315 Straubing, Germany
[b] German Institute of Food Technologies (DIL e.V.), Prof.-von-Klitzing Str. 7, 49610 D Quakenbrück, Germany
[c] Department of Tropical Agriculture and International Cooperation, National Pingtung University of Science and Technology, 91201, Taiwan
[d] Research Center for Food Technology and Processing, National Research and Innovation Agency (BRIN), Gading, Playen, Gunungkidul, 55861 Yogyakarta, Indonesia
[e] Agricultural Product Technology Department, Universitas Sulawesi Barat, Majene 90311, Indonesia
[f] Department of Biological Sciences and Technology, National Pingtung University of Science and Technology, 1, Shuefu Road, Neipu, Pingtung 91201, Taiwan
[g] Centro Tecnológico de la Carne de Galicia, Avd. Galicia N° 4, Parque Tecnológico de Galicia, San Cibrao das Viñas, 32900 Ourense, Spain
[h] Universidade de Vigo, Área de Tecnología de los Alimentos, Facultad de Ciencias de Ourense, 32004 Ourense, Spain
[i] CQM – Centro de Química da Madeira, Universidade da Madeira, Campus da Penteada, 9020-105 Funchal, Portugal
[j] Departamento de Química, Faculdade de Ciências Exatas e Engenharia, Universidade da Madeira, Campus da Penteada, 9020-105 Funchal, Portugal

HIGHLIGHTS

- Mechanism, degradation, and toxicity of PS microplastics, and their effects on the food chain are reviewed.
- PS-MPs are accumulated in the organisms' different organs leading to various adverse dysfunctions.
- PS-MPs affect diverse elements in the food chain spanned from aquatic species to mammals and humans.
- Sustainable plastic waste management policies are required for the prevention of adverse impacts of PS-MPs
- A precise, flexible, and effective methodology for extracting and quantifying PS-MPs needs to be developed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Damia Barcelo

Keywords:
Food chain
Microplastics
Mechanism
Polystyrene
Plastic pollution
Toxicity

ABSTRACT

Polystyrene (PS) is a crucial material for modern plastic manufacturers, but its widespread use and direct discard in the environment severely affect the food chain. This review provides a detailed study on the impact of PS microplastics (PS-MPs) on the food chain and the environment, including information on their mechanism, degradation process, and toxicity. The accumulation of PS-MPs in organisms' different organs leads to various adverse reactions, such as reduced body weight, premature deaths, pulmonary diseases, neurotoxicity, transgenerational issues, oxidative stress, metabolic alterations, ecotoxicity, immunotoxicity, and other dysfunctions. These consequences affect diverse elements in the food chain, spanning from aquatic species to mammals and humans. The review also addresses the need for sustainable plastic waste management policies and technological developments to prevent the adverse impacts of PS-MPs on the food chain. Additionally, it emphasizes the importance of developing a precise, flexible, and effective methodology for extracting and quantifying PS-MPs in food, considering their characteristics like particle size, polymer types, and forms. While several studies have focused on the toxicity of polystyrene microplastics (PS-

* Correspondence to: S.A. Siddiqui, Technical University of Munich Campus Straubing for Biotechnology and Sustainability, Essigberg 3, 94315 Straubing, Germany.
** Correspondence to: J.S. Câmara, CQM – Centro de Química da Madeira, Universidade da Madeira, Campus da Penteada, 9020-105 Funchal, Portugal.
E-mail addresses: S.Siddiqui@dil-ev.de (S.A. Siddiqui), jsc@staff.uma.pt (J.S. Câmara).

http://dx.doi.org/10.1016/j.scitotenv.2023.164531
Received 18 April 2023; Received in revised form 26 May 2023; Accepted 27 May 2023
Available online 31 May 2023

MPs) in aquatic species, further investigation is required to understand the mechanisms by which they are transferred across multiple trophic levels. Therefore, this article serves as the first comprehensive review, examining the mechanism, degradation process, and toxicity of PS-MPs. It presents an analysis of the current research landscape of PS-MPs in the global food chain, providing insights for future researchers and governing organizations to adopt better approaches to managing PS-MPs and preventing their adverse impacts on the food chain. As far as we know this is the first article on this specific and impactant topic.

Contents

1. Introduction

Global plastic production forecasts point to 34 billion tons by 2050, with <10 % being currently recycled (Geyer, 2020). Plastics often break down into smaller fragments through degradation or fragmentation, weakening the bonds and strength of particles and causing them to become brittle. Ultimately, they break down into a powdered form as microparticles, referred to as secondary microplastics (Stolte et al., 2015). Secondary microplastics include polyethylene, polypropylene, and polystyrene (PS) particles (Hwang et al., 2020; Schymanski et al., 2018). In contrast, despite the raw materials can be the same as secondary microplastics, primary microplastic particles are intentionally manufactured with diameters below 5 μm (Hwang et al., 2020). PS is widely used in various products owing to its high tensile strength, swelling ability, stable chemical properties, regeneration properties, large surface area, and economic feasibility. However, the widespread use of polystyrene microplastics (PS-MPs) in the food chain has raised global concerns regarding marine and human health. PS is extensively used at the industrial level because of its low cost and chemical stability, (Dauvergne, 2018; Weber et al., 2020), mainly in scrubs (Fendall and Sewell, 2009), handwashing soaps (Napper et al., 2015), cleansers (Gregory, 1996), toothpaste, or biomedical products (Sharma and Chatterjee, 2017).

Direct contact between humans and microplastics is a potentially critical concern. This contact can occur through various sources, such as food packaging materials, containers, personal care products, biomedical products, and disposable water bottles. Most industrial-scale manufacturing involves the use of single-use plastics, which pose environmental and health concerns. For instance, facial scrubs used for exfoliation contain between 4594 and 94,500 microplastic particles. Similarly, all body exfoliants contain microplastics that pass through the sewage system and filtering them requires high-throughput management (Fendall and Sewell, 2009; Napper et al., 2015). Studies have demonstrated adverse effects resulting from the consumption of microplastics in the food chain, such as in marine invertebrates. For example, oysters (*Magallana gigas*, formerly *Crassostrea gigas*) substantially increased their consumption of microalgae and nutrient absorption when exposed to polystyrene microbeads (Korez et al., 2019). Therefore, this review focuses on PS-MPs, how they are formed and dispersed in the environment and how they are assimilated in the different trophic levels of the food chain. The mechanisms involved in the degradation process and possible strategies for the prevention of this problem will be also discussed.

2. Overview of PS-MPs

2.1. Polystyrene microplastics

Plastic materials measuring <5 mm are often classified as microplastics. Owing to their small size, microplastics can rapidly interact with organic and inorganic contaminants in the environment, such as heavy metals, organic matter, or microorganisms. These contaminants bind to tiny particles of microplastics and act as a medium to transfer pollutants to the environment in different forms (Wu et al., 2019). Earlier studies have shown that brittle pieces of plastic, such as PS spheres, are attached to organisms such as diatoms and hydroids in the coastal waters of Southern New England (Carpenter and Smith Jr., 1972). Since then, plastic contamination of oceans has been described in many places, such as the report of metals, such as aluminium, iron, and manganese, along with other trace metals from the microparticles, found on the beaches of Southwest England near the coastline (Yang et al., 2013). This is a global problem because organic contaminants can be absorbed by the smaller plastic particles in seawater, affecting distant places, such as the Arctic Ocean (Bergmann et al., 2022). The accumulation of PS-MPs in different organs of organisms causes various adverse reactions, including reduced body weight, premature deaths, pulmonary diseases, neurotoxicity, transgenerational issues, oxidative stress, metabolic alterations, ecotoxicity, immunotoxicity, and other kinds of dysfunctions (Besseling et al., 2013; Dimitriadi et al., 2021; Ding et al., 2018; Qiang and Cheng, 2021). For instance, PS-MPs can accumulate in the brain cells of red tilapia, the circulatory system of mussels, and the gut of marine medaka (Ding et al., 2018). Recent studies have indicated that exposure to microplastics of different sizes disturbs the composition of the gut microbiome, affecting the metabolism and resulting in long-term inflammatory responses, intestinal dysfunctions, and alterations in lipid metabolism in zebrafish and mice in laboratory conditions (Wan et al., 2019).

It is a well-known fact that microplastics, in the form of plastic debris, are readily released into the environment and are considered to be

ubiquitously present in the most diverse habitats in soil and ocean sediments, ultimately being integrated into the food chain (Fig. 1) (Liu et al., 2021; Wang et al., 2019a). The size of PS-MPs in the environment can range from 0.5 to 500 μm, and they can be easily consumed by several organisms because of their small size, ultimately affecting humans through the food chain (Cappello et al., 2021; Zheng et al., 2021; Zhu et al., 2020). Neurotoxicity is the major toxicity reported in various aquatic animals owing to the accumulation of PS-MPs. According to previous studies, this toxicity is not only focused on a single generation but can also pass to another generation, indicating transgenerational toxicity. For instance, exposure to PS-MPs resulted in physiological changes in *C. elegans* during subsequent generations (Chen et al., 2021).

2.2. Mechanism of microplastic formation in the environment

The chemical formula of PS is $(C_8H_8)^n$, which is derived from styrene. PS is highly susceptible to natural and artificial weathering, which causes the phenyl ring to become excited when exposed to UV light. This excitation energy is then transmitted to the closest C—H bond, resulting in the cleavage of hydrogen and the creation of a polymer radical. Additionally, ketones and olefins can cause cross-linking and chain scission degradation (Singh and Sharma, 2008; Yousif and Haddad, 2013). Thermooxidation and photo-oxidation degradation processes produce oligomers of styrene, which are found in marine sources as contaminants. Apart from that, abiotic mechanisms consider PS to be a long-lasting polymer, and the rapid degradation that occurs in other microplastics is not observed in PS microplastics (Beyler and Hirschler, 2002; Gewert et al., 2015) (Fig. 2). Therefore, temperatures that exceed the temperature of the marine environment can be used to induce oxidative reactions. However, this is not environmentally sound, and the reaction pathways and products obtained from the degradation require more quantitative extrapolation.

It is important to assess the possibility of microplastic particle accumulation, retention time, and movement in the food chain. However, the translocation of microplastic in biotic sources requires more refined analytical methods for quantification because of their complex physiological characteristics (Elizalde-Velazquez et al., 2020). The biotic degradation mechanisms of PS-MPs are considered insignificant compared to abiotic mechanisms because the durability of abiotic sources is longer than that of biotic sources, which eventually undergo biodegradation (Gewert et al., 2015). Microplastic decomposition in soil affects plant growth and development, as well as the microbial community, by altering pH and modulating other soil properties. However, more in situ experiments are required to further assess the potential adverse effects, and major challenges, such as sampling, classification, and analysis, remain with microplastics entering plants and soil (Rillig et al., 2019).

Other known mechanisms involve the impact of the accumulation of PS-MPs, such as oxidative stress caused by the imbalance between the production and accumulation of oxygen reactive species (ROS) in different cells. Oxidative stress plays an important role in the underlying mechanism of lipid peroxidation, leading to cell apoptosis (Yoo et al., 2021). Therefore, the ROS response can damage cells and their metabolic pathways along with denaturing proteins and DNA.

2.3. Degradation of PS to particles

The mechanism involves degradation pathways, and the resulting products depend mostly on the polymer type of microplastics. PS-MPs are difficult to degrade because they consist of phenyl moieties attached to long linear alkanes, which tend to enter the food chain and interact with organic contaminants. This indicates an alarming situation at environmental and food production or consumption levels. Therefore, it is highly recommended to seek degradation possibilities and some biotic and abiotic degradation methods are discussed in this section (Kedzierski et al., 2020).

Biodegradation is the process of degrading plastic debris with the help of microorganisms, mostly bacterial species, and involves the following steps: I) film formation; II) colonization; III) bio-fragmentation; IV) assimilation; V) mineralization (Albertsson and Karlsson, 1993). The extracellular film consists of biofilm formation, which allows bacteria to form polystyrene fragments in the presence of water. Microorganisms absorb the film and disrupt the physiochemistry of the plastic debris following the colonization with distortion. Additionally, some bacterial strains increase the metabolic processes in the adsorption, desorption, and destruction of microplastics (Mahmud et al., 2022; Rummel et al., 2017). Some studies have indicated that microbial strains found in soils, *Pseudomonas lini* JNU01 and *Acinetobacter johnsonii* JNU01, support non-carbonaceous nutrient media, confirming PS as the only source of carbon. The bacterial species showed 3-fold growth at the site of the PS decomposition process, which affirms that they help accelerate the process of degradation (Kim et al., 2021).

Typically, heteroatomic polymers (such as polyethylene terephthalate and polyurethane) can be degraded with photooxidation, hydrolysis, and

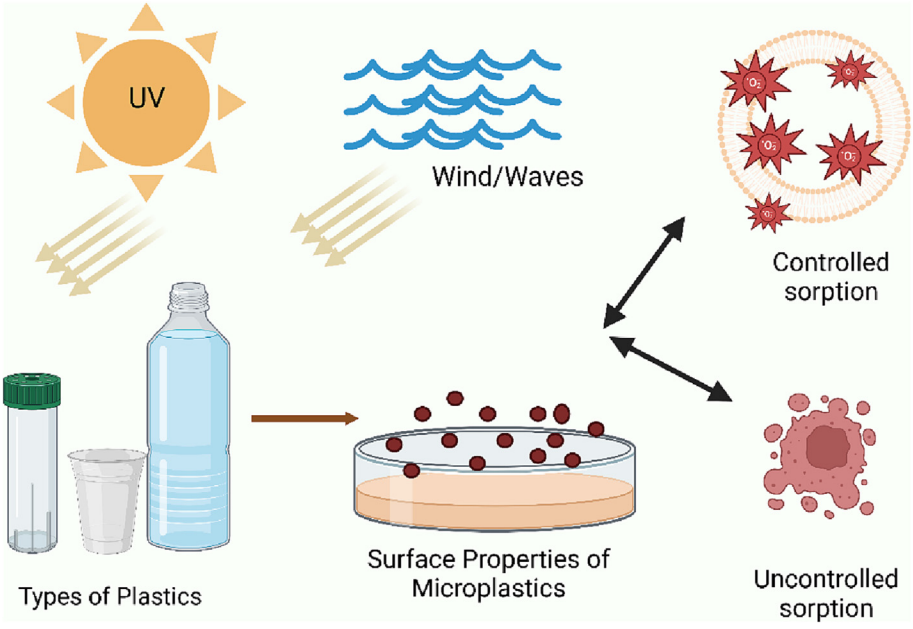


Fig. 1. Changes in surface properties of PS-MPs promote the formation of plastic debris that can then be easily dispersed in the environment through sorption mechanisms, being ultimately integrated into different trophic levels of the food chain (Created with BioRender.com).

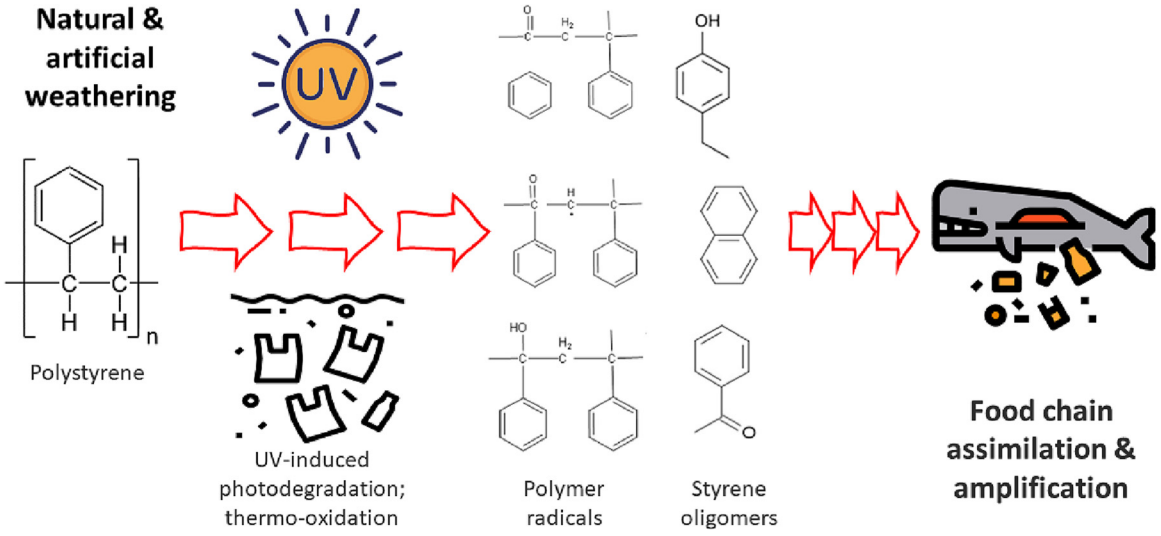


Fig. 2. Overview of the main mechanisms of PS formation and assimilation in the food chain.

biological degradation. However, PS has a C—C backbone polymer that is inert to hydrolysis, prevents rapid degradation and is susceptible to thermal oxidation, requiring regulated conditions and temperatures to occur (Huffer et al., 2018; Krueger et al., 2015; Singh and Sharma, 2008). Therefore, a group of scientists has recently developed an alternate approach with microbially driven Fenton reactions that follow alternate anaerobic and aerobic cycles to fasten the degradation of PS particles. The faster degradation of PS-MPs is stimulated by the dark production of hydroxyl radicals (·OH), and this process is microbially driven and attributed to the positive correlation with the iron redox process that promotes natural thermal oxidation. Additionally, large amounts of organic matter act as carbon sources available in the natural environment for iron-reducing microorganisms (Song et al., 2020). Biodegradation has also been facilitated by plastic-eating insects, such as the wax moth *Galleria mellonella*, which can potentially degrade PS-MPs under in vivo conditions through a mechanism of depolymerisation and complete digestion into PS powder form. The enzymes present in the gut microbiota play crucial roles in the biodegradation of PS particles (Shuai and Zheng, 2022). In another similar insect-mediated biodegradation study, *Zophobas atratus* larvae degraded PS in a 28-day test. The mechanism involves broad depolymerisation and microbial enzymes residing in the gut, including arylesterase and serine hydrolase (Peng and Zhang, 2020). In another interesting study, the land snail *Achatina fulica* degraded 18.5 mg of PS in four weeks, confirming the potential of soil animals to disintegrate microplastics (Song et al., 2020).

The generation of secondary microplastics requires the fragmentation of leftover plastics with ultraviolet radiation, which creates even more concern because debris or leftover are created from primary plastic materials and enter the ocean and soil system to break down into meso- and macroparticles. The process of fragmentation begins with ultraviolet radiation from sunlight through photooxidation and weathering combined with other physical forces that break down plastic material into microparticles (Hwang et al., 2020; Schymanski et al., 2018). Likewise, UV-induced microplastic ageing dramatically oxidises PS-MPs surfaces, resulting in small cracks that improve the ability of the polar contaminant ciprofloxacin to bind to them. The main hydrophilic mechanisms for ciprofloxacin adsorption include electrostatic interactions, intermolecular hydrogen bonds, and partitioning (Huffer et al., 2018).

3. Characteristics of PS-MPs found in the food chain

Plastics are high molecular-weight organic polymers generated by the polymerisation of monomers derived from oil, gas, or coal (Koelmans et al., 2014). The characteristics of PS-MPs are defined based on their morphologies, aggregation, and charges, with the most important issue being the interaction of microparticles with cell surfaces. For instance, smaller particles tend to aggregate quickly due to Van der Waals interactions with sodium and calcium ions in the buffer under scanning microscopic images. Similarly, zeta potential values were determined to understand the charges on PS-MPs. If the value is close to zero, the microparticles are unstable and polydisperse in the medium. The formation of aggregates indicates that smaller particles carry less charge than larger particles at a certain pH, and PS particles with small negative charges usually form uniform aggregates via clustering in the buffer solution (Hwang et al., 2020). Additionally, PS particles can interact with the soil surface and enter different layers via tillage, mulching, ingestion by earthworms, or irrigation sources (Kim et al., 2021). Electron microscopic studies have found that the surface of PS-MPs is porous and consists of several folds, allowing them to easily absorb other contaminants. The abundance of MPs in the environment can be related with different properties, such as density, shape, or size of the polymer and attached pollutants (Zhang et al., 2018). Different classification criteria were followed by different researchers to determine the size distributions depending on the type and area in which PS-MPs were detected. Smaller PS-MPs are ubiquitously present in estuaries and other water bodies (Wang et al., 2019b; Yoo et al., 2021), and these particles with smaller diameters cause significant changes in the pro-inflammatory and cytokine release in the immune cells and reproductive organs of mice in laboratory conditions (Hou et al., 2021a; Hwang et al., 2020). Similar behaviour has been observed in higher aquatic plants and animals with higher genotoxicity and oxidative damage with smaller PS particles (Jiang et al., 2019). Table 1 summarises the studies based on the characteristics of PS-MPs. Therefore, a standardised approach is required for the measurement and documentation of the size distribution data in microplastics.

Microplastic shapes are primarily determined by their morphological characteristics and are classified into fibres, films, foams, and fragments, each made of different polymer types, such as polypropylene (PP), low-density polyethylene (LDPE), polyethylene terephthalate (PET), PS, and polycarbonate (Lozano et al., 2021). As shown in Table 1, most PS microparticles are spherical, forming aggregates as microspheres. The shape of microplastics negatively affects the aggregation of molecules, reducing their stability. Additionally, shapes indicate the basic materials from which microplastics are generated and form aggregates (Yoo et al., 2021; Zhao et al., 2020). In soil, the shape of PS microparticles significantly affects microbial activity and plays a crucial role in determining soil properties (Lozano et al., 2021).

Another characteristic of microplastics is their colour, which is transparent in short-lived plastic products, such as food packaging materials, plastic bags, cups, or bottles. These microplastics are prevalent in the market and other sources such as water and soil (Su et al., 2018). The electrostatic

Table 1
Characteristics of PS-MPs from different sources and their immune responses.

Contaminated sample	PS particles characterization (shape, size & surface charge)	PS uptake and impact	Cytokine profiles	Reference
Immune cells, food & food containers, biomedical products & drinking water	Aggregated small & negatively charged microspheres of 460 nm, 1, 3, 10, 40 & 100 μm	receptor-mediated small particles (<700 nm) endocytosis; higher particles taken up via phagocytosis	↑TNF-α secretion (<1 μm particles PS treatment); significant change of IL-6 secretion (<10 μm PS at 500 μg/mL)	(Hwang et al., 2020)
Brackish water flea *Diaphanosoma celebensis*	negatively charged (sulfate ester anionic charge) 0.05, 0.5, and 6- μm microspheres	Size-dependent oxidative stress	Not reported	(Yoo et al., 2021)
Ovary tissue	0.5 μm negatively charged near-spherical particles with good dispersibility	Oxidative stress in the cells	Release of the inflammation-associated factor NLRP3 inflammasome, activating Caspase-1 and eventually maturing the effector pro-inflammatory cytokines	(Hou et al., 2021b)
Fish meal LDPE & PET	negatively charged & spherical (509, 564 and 632 μm)	Oxidative stress	No cytokine response	(Castelvetro et al., 2020)
Lung epithelial BEAS-2B cells	Spherical, negatively charged & rough surface; 1.72 ± 0.26 μm	Damage in the lung epithelial cells	Pro-inflammatory cytokine response	(Dong et al., 2020)
Spermatogenesis in mice	Roughly spherical & negatively charged; 5 μm	Atrophy, shedding, & apoptosis of sperm cells at all levels of the testis	↑Pro-inflammatory NF-κB and interleukin (IL)-1β & IL-6, ↓anti-inflammatory Nrf2/HO-1	(Hou et al., 2021a)
C57BL/6-mated BALB/c mice	Intact and relatively smooth 10 μm spherical particles	↓number and diameter of uterine arterioles	↓natural killer cells; ↑helper T cells in the placenta; cytokine secretion shifted towards an immune-suppressive state	(Hu et al., 2021)
Marine mussels	Spherical, rough surface microbeads (2.0 μm)	oxidative stress damage & immunotoxicity	Negligible acute toxicity & low environmental risk for short-term exposure	(Huang et al., 2021)
Vicia faba root tips	Spherical & smooth surface 5 & and 100 nm particles (10, 50 and 100 mg/L PS-MPs; 48 h incubation)	↓*V. faba* roots;↑SOD and POD enzymes activity	100 nm PS-MPs induce higher genotoxic & oxidative damage	(Jiang et al., 2019)
Accumulation in mice testis	Spherical & negative charged 0.5, 4 and 10 μm fluorescent particles	Induce spermato-genetic defects, ↓testosterone levels, testicular inflammation, & destruction of the mice BTB	↑pro-inflammatory genes expression	(Jin et al., 2021)
Cardiovascular system exposure	0.5 mm smooth & spherical particles at 0.5, 5 and 50 mg/L; 90 days treatment on 32 male Wister rats	heart fibrosis & cardiac dysfunction	Induced apoptosis of cardiomyocytes & activated signalling pathway through oxidative stress	(Li et al., 2020c)

Legend: BTB - Blood-testis barrier; LDPE - Low-density polyethylene; PET - polyethylene terephthalate; POD -Peroxidase; PS - polystyrene; SOD - superoxide dismuta.

interactions of PS particles are influenced by the heterogeneous surface charge and depend on the mutual orientation of the particles (Ramsperger et al., n.d.). Furthermore, studying the physicochemical properties of microplastics could lead to the development of remediation methods; however, more research is needed to understand the extent to which surface properties affect the behaviour of microplastics.

4. Interaction of PS-MPs with aquatic animals

PS-MPs, as pollutants, have become a major environmental problem in recent years due to their ability to interact with other organisms and systems, posing a threat to the ecosystem. Although wastewater treatment can remove microplastics from water, a significant amount of particle debris remains and passes through freshwater bodies along with the effluent, resulting in harmful effects (Fendall and Sewell, 2009; Sharma and Chatterjee, 2017). Therefore, microplastics coexist with other contaminants, forming chemical interactions or altering their characteristics in different forms by absorption, and acting as carriers of contaminants in the food chain (Pan et al., 2021; Rochman et al., 2013). Owing to their considerable adsorption capacity, microplastics can act as carriers for both inorganic and organic contaminants in the environment (Kinigopoulou et al., 2022). Organic pollutants such as pesticides, PAHs, and other toxic additives can be transported and deposited by microplastics, thus making associations between microplastics and persistent organic pollutants very common in the environment (Gateuille and Naffrechoux, 2022; Kinigopoulou et al., 2022). Moreover, modified microplastics can show strong adsorption performance for some contaminants under the influence of pollutants in the environment (Zhao et al., 2022). This occurs because the interaction of microplastics with organic pollutants alters their environmental behaviour, including their adsorption, degradation, and toxicity (Budhiraja et al., 2022). Accordingly, recent studies have shown that microplastics can act as carriers for hydrophobic organic chemicals, antibiotics, and heavy metals (Kinigopoulou et al., 2022). For instance, researchers have found that PS-MPs adsorb As (III) via electrostatic forces or non-covalent interactions among the bonds between the surface of PS-MPs and arsenic (Gao et al., 2021). It has also been hypothesized that persistent organic pollutants (POPs) in microplastics may pose a risk to aquatic organisms (Koelmans, Besseling et al., 2013). PS particles have the characteristic of aggregating in the presence of high salt concentration; thus, they are expected to aggregate readily in seawater or oceans. Their interactions with various impurities can be harmful to aquatic animals and may have negative consequences for humans. Microplastics with a diameter of <1.5 μm, when absorbed, can cause potential damage at cellular levels directly (Hwang et al., 2020). The different modes of interaction with the PS-MPs are shown in Fig. 3. There are several types of pollutants, such as heavy metals, that can be adsorbed by PS-MPs, although environmental factors affect these adsorption behaviours. Owing to interactions between MPs and microorganisms, antibiotic resistance genes (ARGs) are released when PS-MPs bind to the surface of microorganisms, which has an impact on ARG movement in the environment. The ecotoxicological effects of PS-MPs and their co-exposure to other pollutants impose ecological effects and human health risks (Song et al., 2022).

5. Potential toxicity of PS-MPs

The acute, chronic, sub-chronic, and genotoxic effects caused by PS-MPs in organisms belonging to different levels of the food chain are highly heterogeneous, making it difficult to measure toxicity. Toxic effects are often measured by considering differences among particles in terms of PS size and shape, either in freshwater organisms or terrestrial systems. The PS particle is reported as particle number per litre, while toxicity is reported as grams per litre. Furthermore, most of the studies in Table 2 use gram units for better understanding. Additionally, most authors have used the following equation:

$$\text{MPs (particles/L)} = \text{TMPs (particles/L)} \times \text{Cx (mg/L)}/\text{C (mg/L)} \quad (1)$$

where TMPs is the total number of microplastics in the stock solution, Cx is the concentration (x) of microplastics in the experiment, and C is the

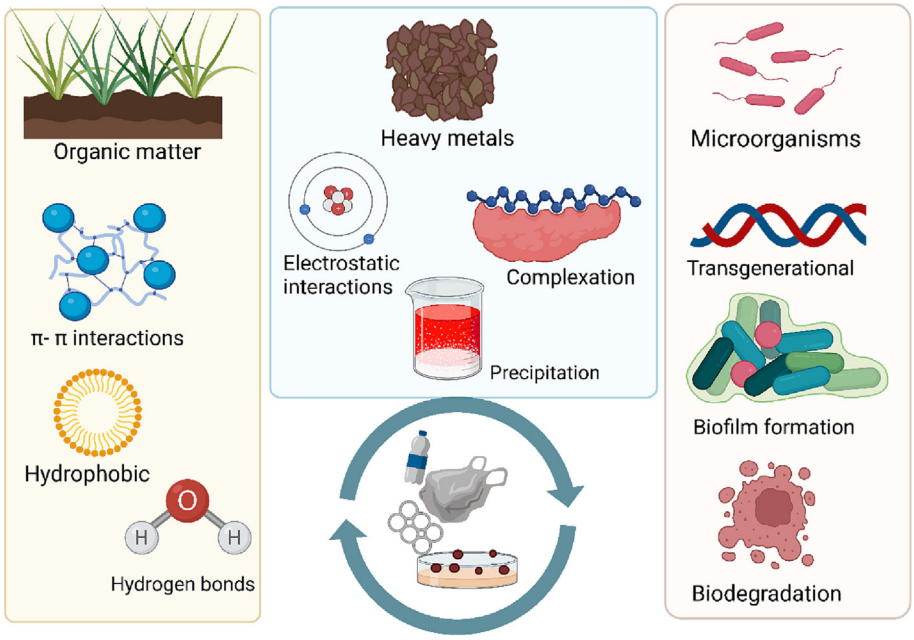


Fig. 3. Types of interactions of microplastic particles with other contaminants, including organic matter, pesticides, heavy metals, and microorganisms (created with Biorender.com).

concentration of microplastics in the stock solution (Li et al., 2018; Pivokonsky et al., 2018; Ziajahromi et al., 2017).

According to Sun and his colleagues (Sun et al., 2021), toxicity based on charges often manifests in terms of electro-physiological changes, such as depolarization of mitochondria, where larger particles are more effective than smaller particles. Smaller particles of PS-MPs can be degraded by lysosomal enzymes through entrapment (Sun et al., 2021), but larger particles of PS can escape lysosomes or are randomly distributed in the cytoplasm, leading to depolarisation of mitochondria and ultimately resulting in apoptosis of cells (An et al., 2021). Other investigators have found that exposure to PS-MPs in the diet of aquatic animals, such as Japanese medaka, causes structural and functional damage to organs and decreases reproductive ability.

PS-MPs also directly affect the innate immune response and damage the ability of cells to fight against pathogens, leading to bacterial and viral agents entering the bloodstream and causing the death of the animals. PS-MPs cause alterations at the biological and genetic levels, resulting in the failure of multiple systems in the body (Li et al., 2020c). Specifically, Li et al. (2020c) reported that PS-MPs cause structural damage and apoptosis of the myocardium and lead to collagen proliferation in the heart, which could induce oxidative stress and activate fibrosis-related Wnt/b-catenin signalling pathway leading to cardiovascular toxicity. PS-MPs have also been shown to cause ovarian fibrosis and decrease the level of anti-Müllerian hormone in the granulosa cells of rat ovaries (An et al., 2021). In addition, exposure to PS-MPs has been linked to male reproductive dysfunctions in mice and inhibition of angiogenic tube formation in human umbilical vein endothelial cells (Lee et al., 2021). PS-MPs have also been found to trigger endoplasmic reticulum stress in the liver of mice, leading to potential hepatotoxicity (Pan et al., 2021). Overall, the diverse examples presented in Table 2 make evident the toxic effects of PS-MP along the food chain, from the small *Daphnia magna* to humans.

6. Future prevention

There is ample evidence indicating that there is no standard protocol for identifying, extracting, and quantifying PS-MPs in the food chain. Therefore, it is highly recommended to develop a precise, flexible, and effective methodology for the extraction and quantification of these particles in food, considering particle size, polymer types, and forms, along with reducing the amount of plastic used for future prevention. Furthermore, PS-MPs in the food chain are not precisely understood. There is a lack of studies on the mechanism of action in numerous toxicological studies, and this topic needs to be adequately explored. Every study is limited to in vitro experiments; however, the actual impact on the food chain can only be seen in the actual setup. Because microorganisms are particularly important in the degradation of plastics, this area can be useful to explore the possible ways of preventing and mitigating PS pollution in the global food chain. The bioavailability and bioaccumulation of PS-MPs in the food chain could have direct or indirect effects on both humans and the entire ecosystem. Scientists around the globe are concerned with the impact of plastic waste on terrestrial and aquatic ecosystems, and the issue of marine plastic pollution has recently attracted global attention, but there are still mismanagement and technological setbacks. There is a dire need for high-throughput technological studies of the anticipated problems of micropollutants. Recent efforts in some countries tend to impose restrictions on single-use plastics and microplastics in personal care and cosmetic products. However, at the industrial scale, these products might be expensive; therefore, a scientific approach for chemical industries is needed to tackle the problem of reducing costs and effort. The other important issue is the direct release of microplastic products into household-based systems, which eventually enter major water bodies of rivers and lakes and ultimately pollute the oceans. Therefore, water management strategies and awareness are two key factors that can prevent environmental microplastic pollution from entering the food chain. As a prevention strategy, effective legislation, and policies for microplastic management must be considered as this issue has been neglected by policymakers. Government institutions must collaborate with private institutions as public-private partnerships to explore the enforcement of high microplastic releases and to help with treatment costs in the manufacturing process.

7. Conclusion

With the increasing demand for plastics every year, most of them end up in freshwater and marine ecosystem. Plastic products tend to break down into smaller particles through natural weathering processes, creating microplastics, whereas others are in the form of small particulate substances. The analysis indicated that PS-MPs enter the food chain through different pathways and from a wide array of sources. Studies have shown

Table 2
Major toxic effects of PS-MPs on different microorganisms.

Microorganisms	Type of PS-MPs contamination or exposure (size, concentration)/ studied effect	Findings	Toxic effects on a food source (fish or other sea products)	Reference
Daphnia magna	15 μm /survival, growth, and reproduction	The significant decline of *D. magna* suggests stressful environmental conditions on invertebrate communities	Chronic toxicity for both adults and neonate *D. magna* revealed that effects were related to food containing PS-MPs.	(Aljaibachi et al., 2020)
Granulosa cells (GCs) of rat ovary	0.5 μm (0, 0.015, 0.15 and 1.5 mg/d) / 90 days exposure (Wistar rats)	PS-MPs could enter GCs, causing a reduction of growing follicles and decreasing the level of anti-Müllerian hormone (AMH)	PS-MPs toxicity causes ovarian fibrosis through the Wnt/β-Catenin signalling pathway triggered by oxidative stress.	(An et al., 2021)
Mytilus galloprovincialis (Marine mussels Mytilus)	3 μm (50 red particles/mL)/ 72 h	PS-MPs accumulation leads to metabolic changes (antioxidant defence system and energy metabolism)	PS-MPs cause ecotoxicity in aquatic invertebrates, highlighting the potential health risk to aquatic biota.	(Cappello et al., 2021)
Chironomus riparius	1 and 10 mg/L PS-MPs & tire rubber MPs/ 36 h	Overexpression of genes of heat shock proteins (HSP) affected the expression of manganese superoxide dismutase (SOD)	Potential ecotoxicity in aquatic organisms	(Carrasco-Navarro et al., 2021)
Caenorhabditis elegans	0.1–100 mg/L exposure of parental generation (F0)	Decreased head thrash and body bends in F0 and subsequent generations	Case of transgenerational neurotoxicity induced by PS-MPs.	(Chen et al., 2021)
P. helgolandica var. *tsingtaoensis* and freshwater microalgae *S. quadricauda*	10 mg/L (1.0, 2.0, 3.0, 4.0, & 5.0 μm diameter)	1.0–2.0 μm PS-MPs exposure caused a significant reduction in the density of microalgae and influenced photosynthesis	Cellular internalization of MPs in phytoplankton, and eco-toxicity of MPs in the aquatic ecosystem.	(Chen et al., 2020)
Zebrafish heart	3–12 μm food-enriched particle / 21 days	Significant decrease in heart function and swimming competence, oxidative stress indices and metabolic changes	Affected fish activity and fish fitness thus PS-MPs act as a potent environmental pollutant	(Dimitriadi et al., 2021)
Freshwater fish red tilapia (*Oreochromis niloticus*)	0.1 mm /1, 10, & 100 mg/L, 14 days	Inhibition of neuromuscular Acetylcholinesterase (AChE) synapses activity in the fish brain	Potential neurotoxicity of PS-MPs to freshwater fish	(Ding et al., 2018)
Human lung epithelial BEAS-2B	1.72 ± 0.26 μm	PS-MPs can cause cytotoxic and inflammatory effects in BEAS-2B cells by inducing ROS formation	High risk for chronic obstructive pulmonary disease (lung diseases)	(Dong et al., 2020)
Daphnia magna (DM) and *Pimephales promelas* (PP)	6 μm / 5 days in the gastrointestinal (GI) tract of DM & PP	PS particles were found within the GI tract of both species with no translocation	Size is an important factor to be considered in translocation studies.	(Elizalde-Velazquez et al., 2020)
Daphnia magna	6 μm / juvenile and adult *Daphnia*	PS-MPs were not acutely toxic to *D. magna* within 48 h but caused added mortality within 120 h	Accumulation in the environment gradually enters the food chain by obstructing non-food particles	(Eltemsah and Bohn, 2019)
Marine medaka (*Oryzias melastigma*)	0.3 & 3.0 μg mg^{-1} / 28 days oral administration, gut microbiota	↓fish body weight & disrupted the liver anti-oxidative status	Major gut-liver axis disruption with toxicological effects of PS-MPs exposure	(Feng et al., 2021)
Spermatogenesis in mice	5 μm / mice spermatogenesis	↓viable epididymis sperm	Abnormal sperm quality in mice was closely related to the proteins associated with transcription factors of innate immunity.	(Hou et al., 2021a)
C57BL/6-mated BALB/c mice	10 μm / pregnant mice	Reduction in number and diameter of uterine arterioles, percentage of decidual natural killer cells	PS-MPs can drastically shift the uterine into immune disturbances during pregnancy	(Hu et al., 2021)
Marine mussels	fluorescent micro-PS beads (green light)	Micro-PS disrupted the amino acid metabolism, particularly phenylalanine metabolism,	PS-MPs lead to oxidative stress and immunotoxicity in mussels	(Huang et al., 2021)
HDFs, PBMCs, and HMC-1	460 nm, 1 μm, 3 μm, 10 μm, 40 μm & 100 μm	Intake of small PS particles induces pro-inflammatory responses in tissues and organs.	Smaller PS particles with diameters of 460 nm and 1 μm affected RBCs.	(Hwang et al., 2020)
Male reproduction (Testis) of mice	0.5, 4 μm & 10 μm	Sperm quality and testosterone level of mice declined after exposure to 0.5 μm, 4 μm, and 10 μm PS-MPs for 28 days	PS-MPs induced male reproductive dysfunctions in mice	(Jin et al., 2021)
Human umbilical vein endothelial cells	0.5 μm	Inhibition of angiogenic tube formation was observed in HUVECs treated with 0.5 μm PS-MPs.	6-h exposure of endothelial cells to PS-MPs represses tube-forming capacity, while 48-h exposure leads to autophagy and necrosis-mediated cytotoxicity.	(Lee et al., 2021)
Chlamydomonas reinhardtii	300–600 nm	PS microplastics had negative effects on algal photosynthesis and decrement in photosynthetic parameter	PS microplastic conditions severely inhibited the growth of *C. reinhardtii* and the highest inhibition rate (IR) was 49.2 %	(Li et al., 2020a)
Marine medaka (*Oryzias melastigma*)	0, 2, 20 & 200 μg/L / fertilized eggs of marine medaka.	High levels of PS-MPs (20 and 200 μg/L) decreased the hatchability, delayed the hatching time, and suppressed the growth	MPs would aggravate the toxicity of organic pollutants	(Li et al., 2020b)
Cardiovascular system of humans	0.5, 5 & 50 mg/L / male Wister rats (32), 90 days	PS-MPs cause structural damage and apoptosis of the myocardium and led to collagen proliferation in the heart	PS-MPs could induce oxidative stress and thus activate fibrosis-related Wnt/b-catenin signalling pathway leading to cardiovascular toxicity	(Li et al., 2020c)
Clams (*Meretrix meretrix*)	200 nm orange carboxylated & 100 nm red aminated microbeads	PS-NH_2 with a smaller hydrodynamic diameter showed greater toxicity to the developing larvae compared to PS-COOH	Stage-dependent toxic effects of MPs on the developing clam larvae	(Luan et al., 2019)
Mice offsprings	0.5 & 5 mm (100 & 1000 mg/L) / during gestation	Two different sizes of PS-MPs increased risks of metabolic disorder in their offspring, and greater effects were observed in 5 mm MPs-treated groups.	Transgenerational toxicity with a high risk of metabolic disorder	(Luo et al., 2019)

(continued on next page)

Table 2 (*continued*)

Microorganisms	Type of PS-MPs contamination or exposure (size, concentration)/ studied effect	Findings	Toxic effects on a food source (fish or other sea products)	Reference
Alga *Raphidocelis subcapitata*, rotifer *Brachionus calyciflorus*, crustacean *Ceriodaphnia dubia* and benthic ostracod *Heterocypris incongruens*	1.0 μm	Acute effects occurred at concentrations of PS-MPs in order of dozens of mg/L in *B. calyciflorus* and *C. dubia* and hundreds of mg/L in *H. incongruens*	The potential genotoxicity and the ROS production due to the PS-MPs were observed in *C. dubia*	(Nugnes et al., 2022)
Liver of mice	5 μm / 0.1 mg/day oral administration	A triggered endoplasmic reticulum (ER) stress in the liver as evidence by activation of the stress-induced homologous proteins	ER stress induced by PS causes oxidative stress leading to potential hepatotoxicity	(Pan et al., 2021)
Toxicity test in (PS)-MPs-mice system	5 or 20 μm / mice's liver, kidney, and gut	Gut had the highest bioaccumulation factor (BCF) of ~8 exposed to 5 μm PS-MPs for ~17 days	Particle size was likely to affect TK/TD behaviour in mice imparting toxicity	(Yang et al., 2019)
Marine medaka (*Oryzias melastigmas*) liver	< 10 μm	83 metabolites were significantly altered in the liver after 10-μm and/or 200-μm PS exposure.	PS exposure triggered the inhibition of several metabolic pathways leading to ecotoxicological effects	(Ye et al., 2021)
Black rockfish *Sebastes schlegelii*	0.5 μm or 15 μm	15-μm PS-exposed fish showed incapable hunting behaviour and exploration competence along with respiration and metabolism stress	Altered behaviour, energy reserve and nutritional quality of fish indicated a potential risk	(Yin et al., 2019)
Brackish water flea *Diaphanosoma celebensis*	0.05, 0.5 & 6-μm diameter beads	Transcriptional level and enzyme activities of antioxidants were modulated, and lipid peroxidation was induced in groups exposed to 0.05 and 0.5-μm beads	PS beads are an important factor for cellular acute toxicity and can induce size-dependent oxidative stress in this species	(Yoo et al., 2021)
Microcystis aeruginosa	1 μm /2–10 mg/L, 12 days	1 μm PS-MPs significantly inhibited the growth in a concentration-dependent manner with an increase in ROS response	Exposure to PS- MPs also altered the transcription levels of microcystin-related genes (mcyA and mcyH), causing more microcystin to be produced by *M. aeruginosa* potentially unsafe for use	(Zhou et al., 2021)
Aquatic species *Salvinia cucullata*	1 μm fluorescent particles (3, 15 & 75 mg/L), glyphosate (5, 25 & 50 mg/L), and mixtures of both / 2–7 days	Reduced relative growth rate and root activity in *S. cucullata*	Adverse effects of microplastics on aquatic plants are potentially associated with different organs exposed to pollution	(Yu et al., 2021)
Utricularia vulgaris plants	1-, 2- & 5-μm fluorescent particles / (15, 70 & 140 mg/L, 7 days	Antioxidative enzyme activities showed that high concentrations of MPs induce high ecotoxicity and oxidative damage to *U. vulgaris*	*U. vulgaris* has the potential to be applied in ecological risk assessments of the effects of MPs on higher aquatic plants.	(Yu et al., 2020)
Clam (*Mactra veneriformis*)	Phenanthrene (20 μgL^{-1} and 50 μgL^{-1}) + PS (17 μm and 150 μm, 1 mg/L)	Phe or PS single stress source could induce oxidative stress in clams.	Under joint exposure stress, the toxicity influence of Phe is still dominant	(Zhang et al., 2021)
Adult zebrafish	5 μm / 20 or 100 μg/L on adult male zebrafish, 21 days	Glycolipid, fatty acid, amino acid and carbon metabolism decreased significantly in the liver at transcription levels	PS-MPs can induce hepatic glycolipid metabolism disorder	(Zhao et al., 2020)
Livers of mice with acute colitis	5 μm / 500 μg/L, 28 days in the livers of mice with acute colitis	PS-MPs exposure induced inflammatory effects and exerted great disturbance on liver metabolites with triglyceride accumulation	Chronic inflammation in the liver with alterations in liver metabolites	(Zheng et al., 2021)
Japanese medaka (*Oryzias latipes*)	10 μm fluorescent particles / 500, 1000, or 2000 μg/g feeding, 10 weeks	Thickening and roughening of epithelium in the headgut and pharynx and cellular alterations in the spleen occurred.	Glomerulopathy and nephrogenesis were observed in exposed fish, increasing in severity with exposure level.	(Zhu et al., 2020)

HUVEC - human umbilical vein endothelial cells; TK/TD - toxicokinetic/toxicodynamic Human Dermal Fibroblasts - HDFs; Human Peripheral Blood Mononuclear Cells - PBMCs; Human Mast Cell line - HMC-1.

that they can accumulate in soil microbes, aquatic plants, and animals, ultimately entering the human body directly or indirectly. The food chain is maintained by the dependency of one organism on another, which can lead to serious detrimental effects because aquatic species are often consumed by humans. Furthermore, these tiny particles interact with organic substances present in the food chain, potentially causing ecotoxicity and altering gene expression. They not only harm the food chain but also alter the genetic makeup of aquatic species and humans. With the adverse effect of transgenerational toxicity on the rise, policymakers and institutions must develop and implement solutions to limit the export of microplastics from cities and landscapes, protect water bodies from pollution loads, restore affected water ecosystems, and reduce exposure to vulnerable populations. Additionally, the adoption and implementation of these solutions must be accompanied by legislation, advanced technologies, economic investments, education, and awareness that could make changes in the coming years and protect the environment. Scientists, policymakers, and the general public must work together to reduce the accumulation of microplastics in terrestrial and aquatic ecosystems by enacting international policies and legislation to reduce microplastic pollution. To achieve sustainable development goals, governments must ensure the implementation of policies related to sustainable plastic waste management, especially aiding microplastics. In addition, they should incorporate technological developments in microplastic waste management strategies and invest in the infrastructure development required for sustainable plastic waste management.

CRediT authorship contribution statement

Shahida Siddiqui Conceptualization, Validation, Formal Analysis, Data Curation, Writing- Original Draft, Writing - Review & Editing, Visualization, Supervision, Resources, Project administration; **Shubhra Singh**: Writing - Original Draft, Formal Editing; **Nur Alim Bahmid**: Conceptualization, Visualization; **Douglas Shyu**: Validation; **Rubén Domínguez**: Writing - Original Draft, Writing - Review & Editing; **Jose M. Lorenzo**: Writing - Review & Editing; **Jorge Pereira**: Validation, Formal Analysis, Data Curation; **José S. Câmara**: Validation, Resources, Funding, Writing - Review & Editing.

Funding

This research was funded by FCT-Fundação para a Ciência e a Tecnologia through the CQM Base Fund - UIDB/00674/2020, and Programmatic Fund - UIDP/00674/2020, and by ARDITI-Agência Regional para o Desenvolvimento da Investigação Tecnologia e Inovação, through the project M1420-01-0145-FEDER-000005 - Centro de Química da Madeira - CQM+ (Madeira 14-20 Program) and the Post-Doctoral fellowship given to JAMP (Project M1420–09–5369-FSE-000001). The authors also acknowledge FCT and Madeira 14-2020 program for the Portuguese Mass Spectrometry Network (RNEM) through PROEQUIPRAM program, M14-20 M1420-01-0145-FEDER-000008).

Data availability

No data was used for the research described in the article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

References

Albertsson, A.-C., Karlsson, S., 1993. Aspects of biodeterioration of inert and degradable polymers. Int. Biodeterior. Biodegradation 31, 161–170.

Aljaibachi, R., Laird, W.B., Stevens, F., Callaghan, A., 2020. Impacts of polystyrene microplastics on Daphnia magna: a laboratory and a mesocosm study. Sci. Total Environ. 705, 135800.

An, R., Wang, X., Yang, L., Zhang, J., Wang, N., Xu, F., et al., 2021. Polystyrene microplastics cause granulosa cells apoptosis and fibrosis in ovary through oxidative stress in rats. Toxicology 449, 152665.

Bergmann, M., Collard, F., Fabres, J., Gabrielsen, G.W., Provencher, J.F., Rochman, C.M., et al., 2022. Plastic pollution in the Arctic. Nat. Rev. Earth Environ. 3, 323–337.

Besseling, E., Wegner, A., Foekema, E.M., van den Heuvel-Greve, M.J., Koelmans, A.A., 2013. Effects of microplastic on fitness and PCB bioaccumulation by the lugworm Arenicola marina (L.). Environ. Sci. Technol. 47, 593–600.

Beyler, C.L., Hirschler, M.M., 2002. Therm. Decomp. Polym. 110–131.

Budhiraja, V., Urh, A., Horvat, P., Krzan, A., 2022. Synergistic adsorption of organic pollutants on weathered polyethylene microplastics. Polymers (Basel) 14.

Cappello, T., De Marco, G., Oliveri Conti, G., Giannetto, A., Ferrante, M., Mauceri, A., et al., 2021. Time-dependent metabolic disorders induced by short-term exposure to polystyrene microplastics in the Mediterranean mussel Mytilus galloprovincialis. Ecotoxicol. Environ. Saf. 209, 111780.

Carpenter, E.J., Smith Jr., K.L., 1972. Plastics on the Sargasso sea surface. Science 175, 1240–1241.

Carrasco-Navarro, V., Muniz-Gonzalez, A.B., Sorvari, J., Martinez-Guitarte, J.L., 2021. Altered gene expression in Chironomus riparius (insecta) in response to tire rubber and polystyrene microplastics. Environ. Pollut. 285, 117462.

Castelvetro, V., Corti, A., Bianchi, S., Giacomelli, G., Manariti, A., Vinciguerra, V., 2020. Microplastics in fish meal: contamination level analyzed by polymer type, including polyester (PET), polyolefins, and polystyrene. Environ. Pollut. 273, 115792.

Chen, H., Hua, X., Li, H., Wang, C., Dang, Y., Ding, P., et al., 2021. Transgenerational neurotoxicity of polystyrene microplastics induced by oxidative stress in Caenorhabditis elegans. Chemosphere 272, 129642.

Chen, Y., Ling, Y., Li, X., Hu, J., Cao, C., He, D., 2020. Size-dependent cellular internalization and effects of polystyrene microplastics in microalgae P. helgolandica var. tsingtaoensis and S. quadricauda. J. Hazard. Mater. 399, 123092.

Dauvergne, P., 2018. The power of environmental norms: marine plastic pollution and the politics of microbeads. Environ. Pol. 27, 579–597.

Dimitriadi, A., Papaefthimiou, C., Genizegkini, E., Sampsonidis, I., Kalogiannis, S., Feidantsis, K., et al., 2021. Adverse effects polystyrene microplastics exert on zebrafish heart - molecular to individual level. J. Hazard. Mater. 416, 125969.

Ding, J., Zhang, S., Razanajatovo, R.M., Zou, H., Zhu, W., 2018. Accumulation, tissue distribution, and biochemical effects of polystyrene microplastics in the freshwater fish red tilapia (Oreochromis niloticus). Environ. Pollut. 238, 1–9.

Dong, C.D., Chen, C.W., Chen, Y.C., Chen, H.H., Lee, J.S., Lin, C.H., 2020. Polystyrene microplastic particles: in vitro pulmonary toxicity assessment. J. Hazard. Mater. 385, 121575.

Elizalde-Velazquez, A., Carcano, A.M., Crago, J., Green, M.J., Shah, S.A., Canas-Carrell, J.E., 2020. Translocation, trophic transfer, accumulation and depuration of polystyrene microplastics in Daphnia magna and Pimephales promelas. Environ. Pollut. 259, 113937.

Eltemsah, Y.S., Bohn, T., 2019. Acute and chronic effects of polystyrene microplastics on juvenile and adult Daphnia magna. Environ. Pollut. 254, 112919.

Fendall, L.S., Sewell, M.A., 2009. Contributing to marine pollution by washing your face: microplastics in facial cleansers. Mar. Pollut. Bull. 58, 1225–1228.

Feng, S., Zeng, Y., Cai, Z., Wu, J., Chan, L.L., Zhu, J., et al., 2021. Polystyrene microplastics alter the intestinal microbiota function and the hepatic metabolism status in marine medaka (Oryzias melastigma). Sci. Total Environ. 759, 143558.

Gao, M., Xu, Y., Liu, Y., Wang, S., Wang, C., Dong, Y., et al., 2021. Effect of polystyrene on dibutyl phthalate (DBP) bioavailability and DBP-induced phytotoxicity in lettuce. Environ. Pollut. 268, 115870.

Gateuille, D., Naffrechoux, E., 2022. Transport of persistent organic pollutants: another effect of microplastic pollution? WIREs Water 9, e1600.

Gewert, B., Plassmann, M.M., MacLeod, M., 2015. Pathways for degradation of plastic polymers floating in the marine environment. Environ Sci Process Impacts 17, 1513–1521.

Geyer, R., 2020. Chapter 2 - production, use, and fate of synthetic polymers. In: Letcher, T.M. (Ed.), Plastic Waste and Recycling. Academic Press, pp. 13–32.

Gregory, M.R., 1996. Plastic 'scrubbers' in hand cleansers: a further (and minor) source for marine pollution identified. Mar. Pollut. Bull. 32, 867–871.

Hou, B., Wang, F., Liu, T., Wang, Z., 2021a. Reproductive toxicity of polystyrene microplastics: in vivo experimental study on testicular toxicity in mice. J. Hazard. Mater. 405, 124028.

Hou, J., Lei, Z., Cui, L., Hou, Y., Yang, L., An, R., et al., 2021b. Polystyrene microplastics lead to pyroptosis and apoptosis of ovarian granulosa cells via NLRP3/Caspase-1 signaling pathway in rats. Ecotoxicol. Environ. Saf. 212, 112012.

Hu, J., Qin, X., Zhang, J., Zhu, Y., Zeng, W., Lin, Y., et al., 2021. Polystyrene microplastics disturb maternal-fetal immune balance and cause reproductive toxicity in pregnant mice. Reprod. Toxicol. 106, 42–50.

Huang, W., Wang, X., Chen, D., Xu, E.G., Luo, X., Zeng, J., et al., 2021. Toxicity mechanisms of polystyrene microplastics in marine mussels revealed by high-coverage quantitative metabolomics using chemical isotope labeling liquid chromatography mass spectrometry. J. Hazard. Mater. 417, 126003.

Huffer, T., Weniger, A.K., Hofmann, T., 2018. Sorption of organic compounds by aged polystyrene microplastic particles. Environ. Pollut. 236, 218–225.

Hwang, J., Choi, D., Han, S., Jung, S.Y., Choi, J., Hong, J., 2020. Potential toxicity of polystyrene microplastic particles. Sci. Rep. 10, 7391.

Jiang, X., Chen, H., Liao, Y., Ye, Z., Li, M., Klobucar, G., 2019. Ecotoxicity and genotoxicity of polystyrene microplastics on higher plant Vicia faba. Environ. Pollut. 250, 831–838.

Jin, H., Ma, T., Sha, X., Liu, Z., Zhou, Y., Meng, X., et al., 2021. Polystyrene microplastics induced male reproductive toxicity in mice. J. Hazard. Mater. 401, 123430.

Kedzierski, M., Lechat, B., Sire, O., Le Maguer, G., Le Tilly, V., Bruzaud, S., 2020. Microplastic contamination of packaged meat: occurrence and associated risks. Food Packag. Shelf Life 24, 100489.

Kim, H.W., Jo, J.H., Kim, Y.B., Le, T.K., Cho, C.W., Yun, C.H., et al., 2021. Biodegradation of polystyrene by bacteria from the soil in common environments. J. Hazard. Mater. 416, 126239.

Kinigopoulou, V., Pashalidis, I., Kalderis, D., Anastopoulos, I., 2022. Microplastics as carriers of inorganic and organic contaminants in the environment: a review of recent progress. J. Mol. Liq. 350, 118580.

Koelmans, A.A., Besseling, E., Foekema, E.M., 2014. Leaching of plastic additives to marine organisms. Environ. Pollut. 187, 49–54.

Korez, S., Gutow, L., Saborowski, R., 2019. Feeding and digestion of the marine isopod Idotea emarginata challenged by poor food quality and microplastics. Comp. Biochem. Physiol. C Toxicol. Pharmacol. 226, 108586.

Krueger, M.C., Harms, H., Schlosser, D., 2015. Prospects for microbiological solutions to environmental pollution with plastics. Appl. Microbiol. Biotechnol. 99, 8857–8874.

Lee, H.S., Amarakoon, D., Wei, C.I., Choi, K.Y., Smolensky, D., Lee, S.H., 2021. Adverse effect of polystyrene microplastics (PS-MPs) on tube formation and viability of human umbilical vein endothelial cells. Food Chem. Toxicol. 154, 112356.

Li, J., Liu, H., Paul, Chen J., 2018. Microplastics in freshwater systems: a review on occurrence, environmental effects, and methods for microplastics detection. Water Res. 137, 362–374.

Li, S., Wang, P., Zhang, C., Zhou, X., Yin, Z., Hu, T., et al., 2020a. Influence of polystyrene microplastics on the growth, photosynthetic efficiency and aggregation of freshwater microalgae Chlamydomonas reinhardtii. Sci. Total Environ. 714, 136767.

Li, Y., Wang, J., Yang, G., Lu, L., Zheng, Y., Zhang, Q., et al., 2020b. Low level of polystyrene microplastics decreases early developmental toxicity of phenanthrene on marine medaka (Oryzias melastigma). J. Hazard. Mater. 385, 121586.

Li, Z., Zhu, S., Liu, Q., Wei, J., Jin, Y., Wang, X., et al., 2020c. Polystyrene microplastics cause cardiac fibrosis by activating Wnt/beta-catenin signaling pathway and promoting cardiomyocyte apoptosis in rats. Environ. Pollut. 265, 115025.

Liu, S.Y., Leung, M.M.-L., Fang, J.K.-H., Chua, S.L., 2021. Engineering a microbial 'trap and release' mechanism for microplastics removal. Chem. Eng. J. 404, 127079.

Lozano, Y.M., Lehnert, T., Linck, L.T., Lehmann, A., Rillig, M.C., 2021. Microplastic shape, polymer type, and concentration affect soil properties and plant biomass. Front. Plant Sci. 12, 616645.

Luan, L., Wang, X., Zheng, H., Liu, L., Luo, X., Li, F., 2019. Differential toxicity of functionalized polystyrene microplastics to clams (Meretrix meretrix) at three key development stages of life history. Mar. Pollut. Bull. 139, 346–354.

Luo, T., Zhang, Y., Wang, C., Wang, X., Zhou, J., Shen, M., et al., 2019. Maternal exposure to different sizes of polystyrene microplastics during gestation causes metabolic disorders in their offspring. Environ. Pollut. 255, 113122.

Mahmud, A., Wasif, M.M., Roy, H., Mehnaz, F., Ahmed, T., Pervez, M.N., et al., 2022. Aquatic microplastic pollution control strategies: sustainable degradation techniques, resource recovery, and recommendations for Bangladesh. Water 14, 3968.

Napper, I.E., Bakir, A., Rowland, S.J., Thompson, R.C., 2015. Characterisation, quantity and sorptive properties of microplastics extracted from cosmetics. Mar. Pollut. Bull. 99, 178–185.

Nugnes, R., Lavorgna, M., Orlo, E., Russo, C., Isidori, M., 2022. Toxic impact of polystyrene microplastic particles in freshwater organisms. Chemosphere 299, 134373.

Pan, L., Yu, D., Zhang, Y., Zhu, C., Yin, Q., Hu, Y., et al., 2021. Polystyrene microplastics-triggered mitophagy and oxidative burst via activation of PERK pathway. Sci. Total Environ. 781, 146753.
Peng, B.-Y., Zhang, Y., 2020. Biodegradation of polystyrene and low-density polyethylene by Zophobas atratus larvae: fragmentation into microplastics, gut shift and microbial functional enzymes. J. Clean. Prod. 367, 132–987.
Pivokonsky, M., Cermakova, L., Novotna, K., Peer, P., Cajthaml, T., Janda, V., 2018. Occurrence of microplastics in raw and treated drinking water. Sci. Total Environ. 643, 1644–1651.
Qiang, L., Cheng, J., 2021. Exposure to polystyrene microplastics impairs gonads of zebrafish (Danio rerio). Chemosphere 263, 128161.
Ramsperger A, Rudolph J, Matthias V, Witzmann T. Surface properties of microplastic particles matter for particle-cell-interactions. 332951.
Rillig, M.C., Lehmann, A., de Souza Machado, A.A., Yang, G., 2019. Microplastic effects on plants. New Phytol. 223, 1066–1070.
Rochman, C.M., Hoh, E., Kurobe, T., Teh, S.J., 2013. Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. Sci. Rep. 3, 3263.
Rummel, C.D., Jahnke, A., Gorokhova, E., Kühnel, D., Schmitt-Jansen, M., 2017. Impacts of biofilm formation on the fate and potential effects of microplastic in the aquatic environment. Environ. Sci. Technol. Lett. 4, 258–267.
Schymanski, D., Goldbeck, C., Humpf, H.U., Furst, P., 2018. Analysis of microplastics in water by micro-Raman spectroscopy: release of plastic particles from different packaging into mineral water. Water Res. 129, 154–162.
Sharma, S., Chatterjee, S., 2017. Microplastic pollution, a threat to marine ecosystem and human health: a short review. Environ. Sci. Pollut. Res. Int. 24, 21530–21547.
Shuai, W., Zheng, H., 2022. Complete digestion/biodegradation of polystyrene microplastics by greater wax moth (Galleria mellonella) larvae: direct in vivo evidence, gut microbiota independence, and potential metabolic pathways. J. Hazard. Mater. 423, 127–213.
Singh, B., Sharma, N., 2008. Mechanistic implications of plastic degradation. Polym. Degrad. Stab. 93, 561–584.
Song, X., Zhuang, W., Cui, H., Liu, M., Gao, T., Li, A., et al., 2022. Interactions of microplastics with organic, inorganic and bio-pollutants and the ecotoxicological effects on terrestrial and aquatic organisms. Sci. Total Environ. 838, 156068.
Song, Y., Qiu, R., Hu, J., Li, X., Zhang, X., Chen, Y., et al., 2020. Biodegradation and disintegration of expanded polystyrene by land snails Achatina fulica. Sci. Total Environ. 746, 141289.
Stolte, A., Forster, S., Gerdts, G., Schubert, H., 2015. Microplastic concentrations in beach sediments along the German Baltic coast. Mar. Pollut. Bull. 99, 216–229.
Su, L., Cai, H., Kolandhasamy, P., Wu, C., Rochman, C.M., Shi, H., 2018. Using the Asian clam as an indicator of microplastic pollution in freshwater ecosystems. Environ. Pollut. 234, 347–355.
Sun, R., Xu, K., Yu, L., Pu, Y., Xiong, F., He, Y., et al., 2021. Preliminary study on impacts of polystyrene microplastics on the hematological system and gene expression in bone marrow cells of mice. Ecotoxicol. Environ. Saf. 218, 112296.
Wan, Z., Wang, C., Zhou, J., Shen, M., Wang, X., Fu, Z., et al., 2019. Effects of polystyrene microplastics on the composition of the microbiome and metabolism in larval zebrafish. Chemosphere 217, 646–658.
Wang, Y., Mao, Z., Zhang, M., Ding, G., Sun, J., Du, M., et al., 2019a. The uptake and elimination of polystyrene microplastics by the brine shrimp, Artemia parthenogenetica, and its impact on its feeding behavior and intestinal histology. Chemosphere 234, 123–131.
Wang, Y., Zhang, D., Zhang, M., Mu, J., Ding, G., Mao, Z., et al., 2019b. Effects of ingested polystyrene microplastics on brine shrimp, *Artemia parthenogenetica*. Environ. Pollut. 244, 715–722.
Weber, A., Jeckel, N., Wagner, M., 2020. Combined effects of polystyrene microplastics and thermal stress on the freshwater mussel Dreissena polymorpha. Sci. Total Environ. 718, 137253.
Wu, B., Wu, X., Liu, S., Wang, Z., Chen, L., 2019. Size-dependent effects of polystyrene microplastics on cytotoxicity and efflux pump inhibition in human Caco-2 cells. Chemosphere 221, 333–341.
Yang, Y., Zhang, C., Hu, Z., 2013. Impact of metallic and metal oxide nanoparticles on wastewater treatment and anaerobic digestion. Environ Sci Process Impacts 15, 39–48.
Yang, Y.F., Chen, C.Y., Lu, T.H., Liao, C.M., 2019. Toxicity-based toxicokinetic/toxicodynamic assessment for bioaccumulation of polystyrene microplastics in mice. J. Hazard. Mater. 366, 703–713.
Ye, G., Zhang, X., Liu, X., Liao, X., Zhang, H., Yan, C., et al., 2021. Polystyrene microplastics induce metabolic disturbances in marine medaka (Oryzias melastigmas) liver. Sci. Total Environ. 782, 146885.
Yin, L., Liu, H., Cui, H., Chen, B., Li, L., Wu, F., 2019. Impacts of polystyrene microplastics on the behavior and metabolism in a marine demersal teleost, black rockfish (Sebastes schlegelii). J. Hazard. Mater. 380, 120861.
Yoo, J.W., Cho, H., Jeon, M., Jeong, C.B., Jung, J.H., Lee, Y.M., 2021. Effects of polystyrene in the brackish water flea Diaphanosoma celebensis: size-dependent acute toxicity, ingestion, egestion, and antioxidant response. Aquat. Toxicol. 235, 105821.
Yousif, E., Haddad, R., 2013. Photodegradation and photostabilization of polymers, especially polystyrene: review. Springer Plus 383, 1–32.
Yu, H., Zhang, X., Hu, J., Peng, J., Qu, J., 2020. Ecotoxicity of polystyrene microplastics to submerged carnivorous Utricularia vulgaris plants in freshwater ecosystems. Environ. Pollut. 265, 114830.
Yu, H., Peng, J., Cao, X., Wang, Y., Zhang, Z., Xu, Y., et al., 2021. Effects of microplastics and glyphosate on growth rate, morphological plasticity, photosynthesis, and oxidative stress in the aquatic species Salvinia cucullata. Environ. Pollut. 279, 116900.
Zhang, K., Shi, H., Peng, J., Wang, Y., Xiong, X., Wu, C., et al., 2018. Microplastic pollution in China's inland water systems: a review of findings, methods, characteristics, effects, and management. Sci. Total Environ. 630, 1641–1653.
Zhang, X., Wang, X., Yan, B., 2021. Single and combined effects of phenanthrene and polystyrene microplastics on oxidative stress of the clam (Mactra veneriformis). Sci. Total Environ. 771, 144728.
Zhao, M., Huang, L., Arulmani, S.R.B., Yan, J., Wu, L., Wu, T., et al., 2022. Adsorption of different pollutants by using microplastic with different influencing factors and mechanisms in wastewater: a review. Nanomaterials (Basel) 12.
Zhao, Y., Bao, Z., Wan, Z., Fu, Z., Jin, Y., 2020. Polystyrene microplastic exposure disturbs hepatic glycolipid metabolism at the physiological, biochemical, and transcriptomic levels in adult zebrafish. Sci. Total Environ. 710, 136279.
Zheng, H., Wang, J., Wei, X., Chang, L., Liu, S., 2021. Proinflammatory properties and lipid disturbance of polystyrene microplastics in the livers of mice with acute colitis. Sci. Total Environ. 750, 143085.
Zhou, J., Gao, L., Lin, Y., Pan, B., Li, M., 2021. Micrometer scale polystyrene plastics of varying concentrations and particle sizes inhibit growth and upregulate microcystin-related gene expression in Microcystis aeruginosa. J. Hazard. Mater. 420, 126591.
Zhu, M., Chernick, M., Rittschof, D., Hinton, D.E., 2020. Chronic dietary exposure to polystyrene microplastics in maturing Japanese medaka (Oryzias latipes). Aquat. Toxicol. 220, 105396.
Ziajahromi, S., Kumar, A., Neale, P.A., Leusch, F.D.L., 2017. Impact of microplastic beads and fibers on waterflea (Ceriodaphnia dubia) survival, growth, and reproduction: implications of single and mixture exposures. Environ. Sci. Technol. 51, 13397–13406.