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RESEARCH PAPER

# Overview of microplastics in the environment: type, source, potential effects and removal strategies

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**Abstract**
The introduction of plastic sectors has resulted in the presence of microplastics (MPs) in water systems, which has become a global issue that has attracted scientific and community awareness. MPs can be detected in a variety of sources such as beauty products, manufacturing effluent, or fishing activities. This study examined the repercussions posed by MPs' prevalence on land and marine environments and human health issues. Henceforth, remediation technologies must be introduced to shift out MPs from the water supplies in order to sustain the environmental quality for future generations, the benefits and drawbacks of the technology applied. This study also portrays difficulties encountered in MP research as the hurdles must be mastered in order to properly comprehend the MPs. The cooperation between nations is the most critical aspect in fully tackling MP issues as it can be easily carried by wind or water and its damage can be larger than predicted.

**Keywords** Microplastics · Distribution · Potential effects · Removal efficiency

## Introduction

Plastics are recognised for being incredibly flexible materials that are light, mechanically stable, as well as have excellent thermal and electrical insulating qualities, rendering them resilient and appropriate for usage in hostile environs [1]. Bakelite, the very first artificial plastic, was invented in 1907, heralding the start of the worldwide plastic manufacturing sector. Nevertheless, it was not until the 1950s that worldwide plastic production grew at a rapid pace [2]. Due to its promise and economical price, as well as its suitability for a broad range of commercial and industrial applications, plastics production surged by about 200 times for the following 65 years, exceeding 0.380 billion tonnes in 2015, roughly equivalent to 67% of the global population [1, 2]. Plastics are found in practically every facet of society, including transportation, electronic devices, clothes, and packaging constituents that help convey food, beverages, and other commodities [1]. Plastics are classified into several varieties depending on their ingredients and the materials used in their manufacture [2]. Table 1 lists the types of plastics with their features and applications. The most commonly used and abundant polymers/plastics are high-density polyethylene (HDPE), polyvinyl chloride (PVC), polypropylene (PS), polystyrene (PS), and polyethylene terephthalate (PET). These polymers are also the most commonly found plastics in the environment, especially in marine environments [3, 4]. People consume carbonated drinks and butter almost every day and commonly the bottles and jars are made by polyethylene terephthalate (PET). Other plastic type is HDPE plastic which we use as agriculture tubing, pail, and plastic bottles. The next commonly used plastic is polyvinyl chloride (PVC). PVC can be found in electrical circuits, bottles, and skincare containers. Other type is polypropylene (PP). PP is commonly found in wrapping tape, containers, lawn

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**Table 1** Types of plastics with their uses and features

| Plastic types | Applications | Characteristics | Soften temperature (°C) | Average densities (g/cm$^3$) | References |
|---|---|---|---|---|---|
| Polyethylene terephthalates (PET) | Clothes, food or beverage containers, soft drinks | Robust<br>Transparent<br>Thin | 80 | 1.40 | [45, 65] |
| High-density polyethylene (HDPE) | Agriculture tubing, pail, plastic bottles | Heat resistant<br>Chemicals and water resilient<br>Light impermeable | 75 | 0.95 | [45, 65] |
| Polyvinyl chloride (PVC) | Electrical circuits, bottles, skincare containers | Heat resistant<br>Durable<br>High toxicity | 80 | 1.45 | [45, 65] |
| Polypropylene (PP) | Wrapping tape, containers, lawn appliances, snacks bags | Strong<br>Translucent | 140 | 0.88 | [45, 65] |
| Polystyrene (PS) | CD boxes, plastic tableware, artificial glassware, packaging | Alkaline resistant<br>Moderate tough<br>Brittle<br>Light impermeable | 95 | 1.06 | [45, 65] |

appliance and snack bags. The next type of plastics is polystyrene (PS) which we use every day as packaging foam, food containers, disposable cups, plates, and cutlery.

Due to the expanding plastic manufacture, disposal issues, and human activities, plastic waste has become an impressive burden across worldwide habitats [5]. Table 2 indicates how much plastic waste each country contributes to the environment every year. Asia has been named as the most ocean polluter. According to a report from Jambeck et al. [6], 8 from the top 10 countries ranked by mass of mismanaged plastic waste are Asian countries. China is the largest source of mismanaged plastic that generated 8, 8 MT per year.

Plastic can be classified into 4 types: macroplastics, mesoplastics, microplastics, and nanoplastics. Microplastics (MPs) are micro-scale particles with a primarily manufactured polymeric structure, with size ranging from 5 mm to 1 µm [5, 7]. While MPs have been found since the early 1970s, it is only recently that they have become aware of the spatial distribution and ecological ramifications of this chronic pollution and have begun to investigate them [5]. They are particularly dispersed and identified in terrestrial and aquatic settings, they have already wreaked havoc on marine life, plantations, and humans [5, 7]. As ambient MP concentrations rise, so does the probability of ecosystem exposure, engagement, consumption, and deleterious consequences throughout food webs [5]. As a result, they have emerged as a potential food safety concern and hazard. They also have the ability to disrupt biota in a variety of forms, causing the ecosystem to become screwed up and unbalanced [5, 7]. Hence, the MPs problem has recently gained scientific and social attention, and remediation methods are essential matters that must be deployed to extract MP from water resources in order to secure human health, as consuming water and contaminated food are the most likely source of MPs entering human bodies [7]. This study aims to investigate the relationship between MPs and the environment to comprehend them then come up with a solution to encounter the effects of MP pollution.

**Table 2** Summary of countries that contribute plastic waste to the environment

| Country | Average of mismanaged plastic waste (×10$^6$ kg/year) | Average of plastic marine debris (×10$^6$ kg/year) | References |
|---|---|---|---|
| China | 8820 | 2425 | [6] |
| Indonesia | 3220 | 885 | [6] |
| Philippines | 1880 | 515 | [6] |
| Vietnam | 1830 | 505 | [6] |
| Sri Lanka | 1590 | 440 | [6] |
| United State | 2750 | 75 | [6, 66] |
| Malaysia | 940 | 255 | [6, 67] |

## Type, sources and transport of MPs

During the past few years, MPs have become one of the popular global pollutions, as they can be released into the environment via different sources, as indicated in Fig. 1, some of which are discussed in more depth below [8–10]. This predicament has added stress to human livelihoods and has become a threat to our biosphere, and thus numerous studies and authorities are currently looking into and focussing on this issue before it worsens.

### Type of MPs

MPs are categorised as primary or secondary based on whether they are contrived to be micron-sized or decompose from larger or original polymers [9, 11]. It is a crucial aspect since it can assist in identifying contributory causes and mitigating methods to lessen their ecological consequences. Primary MPs can be defined as elements that are fewer than 5 mm in diameter before entering the environs, they are commonly utilised in commercial products such as cosmeceuticals and textile fibres [9].

While secondary MPs are formed by larger plastic weathering or disintegration due to environmental factors such as wave erosion, temperature variation, ultraviolet (UV) irradiation, alkalinity or polymer type and ageing [9]. When plastics are subjected to UV or solar radiation, they experience weathering degradation and deterioration, losing their tensile properties, discolouring and forming surface fissures, and eventually becoming frail and fragile. Any forces acting, such as waves, wind, or human action, can easily break them down into smaller pieces [10].

### Sources of MPs

Personal care and cosmetic sectors are the key contributors of MPs to the environment [11]. Most exfoliants and cleansers contain MPs in their components to substitute conventionally used materials such as almonds, oats, and corns. It is estimated that an exfoliant can release up to 94,000 MPs in every single application [11, 12]. Based on a previous study, approximately 4000 tonnes of MPs are used in cosmetics across the European Union, including Norway and Switzerland, and these particles are likely to end up in residential wastewater due to their use. Due to their diminutive diameter, these particles have a higher possibility of slipping through wastewater treatment and eventually wind up aquatic ecosystems, lowering fresh water quality and causing harm to nearby organisms. In actuality, wastewater treatment plants (WWTP receive microplastic pollutants through the domestic discharge systems, municipal wastewater, landfill leachates and drainage systems [13, 14], was only applicable to capture 95% of MPs, leaving the rest to be released [15]. The sewage sludge, which is utilised as compost after being treated for wastewater and discovered to contain MPs, is not included in this instance. In recent years, there has been mounting evidence that MPs constitute a hazard to the environment. The usage of MPs in commercial items has recently piqued the interest of scientists and the general public, as MPs present a risk to marine ecology. Nations such as Canada, New Zealand, Ireland, and Sweden have established legislation prohibiting MPs in cosmetic products, with some manufacturing companies already begun to phase them out. Any law or regulation of this nature must aim to minimise or eliminate the release of redundant plastic particles into the surroundings [11].

Fishing, farming, and aquaculture activities could be the causes of MPs contamination in water bodies. According

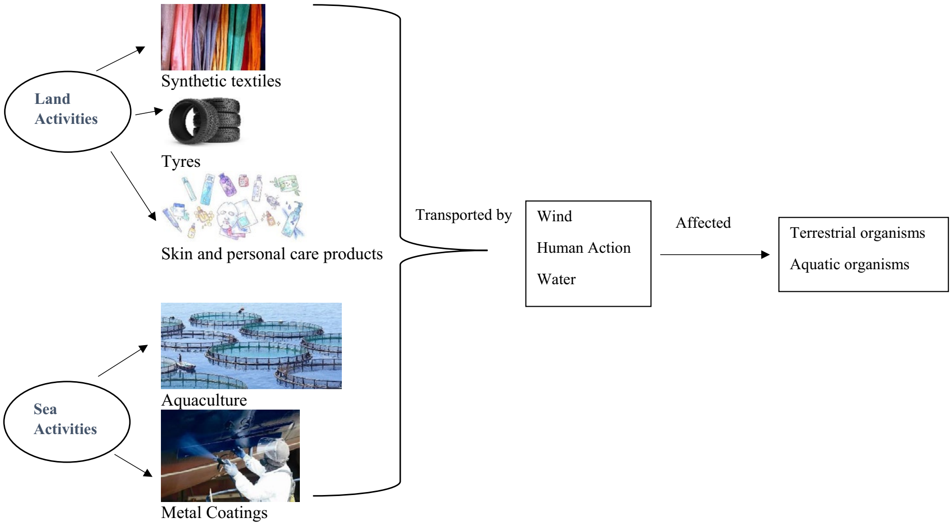

**Fig. 1** Sources of MPs from both land and sea [21]

to studies, agricultural commodities in China employed over 1.20 million tons of plastic elements in 2011. In contrast, sewage sludge is used as fertiliser in farming by having nearly 250,000 and 170,000 tons of MPs in Europe and America, correspondingly [12]. Moreover, plastic mulching is widely used in residential cultivation for heat and moisture preservation, fertiliser engagement, and soil enhancement. This results in abundant plastic in farmed soils, which can be transferred into freshwater ecosystems by water and wind [12, 16, 17]. Factors that affect the translocation and movement of MPs are density, structure, and volume [12]. Furthermore, aquaculture activities are strongly associated with MPs contamination in aquatic systems due to the intricacy of aquaculture settings. Plastics are broadly discovered in fishing equipment, including nets, spawning, farming gadgets, buckets, among other things. As a result, the majority of MPs in aquaculture come from the loss and discard of the fishing plastic implements [12, 18]. Based solely on Norwegian fishing activities, abandoned fishing gear has increased by 3500 tonnes in only 9 years. Consequently, significant quantities of MPs are often identified in fish meals, with over 300 MPs discovered in the samples taken from several brands from Malaysia. Besides, fish medication and animal supplements are also known as sources of MPs as there is an intimate connection between MPs and antimicrobial agents. Hence, their implications for aquaculture habitat bolster the case. The statement above supports that aquaculture activities may have negative repercussions for marine ecosystems and, indirectly, human health [12].

Fibres, either natural or manufactured, are one form of MPs typically observed in the sample collections and have originated in textiles. Polyester is the most famous textile fibre because it is a cost-effective and easy-to-manufacture cotton replacement; yet, it has a significant role in MPs persistence in terrestrial, airborne, and aquatic habitats [19]. MPs are released from synthetic garments mainly due to physical and chemical stressors that textiles experience during the washing practice, causing microfibers to detach from the threads [20]. According to a recent study, the number of fibres emitted per kilogram of laundry could achieve over 110,000 fibres [19]. In the previous 2 decades, global average garment fibres consumption has surged by 80%, attributable to increased synthetic fibre consumption, which has expanded by 300% [19, 20]. This situation causes the overall quantity of fibres entering and travelling through WWTP to undoubtedly rise, proving system technology critical in reducing the environmental impact of MPs [8, 20]. Authorities are presently considering research into better fabrication and vacuum exertion at manufacturing sites and the introduction of additional filters in residential laundry to reduce the presence of MPs in the ecosystem [19].

## Fate and distribution of MPs

If the implications of MPs on ecological processes ought to be wholly comprehended and addressed, the mobility and deposition of MPs must be acknowledged. MPs generally utilised transportation mechanisms to impact populations and ecosystems well beyond where they are introduced, yielding a considerably greater effect than anticipated. MP interaction and consumption by species as well as their consequent incorporation into the food chain are influenced by transport processes, such as MP flow, retention time, and deposition. Besides, transport procedures affect the density of MP contamination and the impact of these particles on creatures [21]. Thus, assessing the fates of MPs in freshwater habitats together with their deliveries is essential for determining their consequences and delivery impacts [12, 21]. Table 3 depicts the average MP concentration at different regions. Through the different studies regarding

**Table 3** The average concentration of MP discovered in different regions

| Region (water) | MP concentration | References | Region (sediment) | MP concentration | References |
|---|---|---|---|---|---|
| Java island (Indonesia) | 405 particles/L | [3] | Jagir estuary (Indonesia) | 253 particles/kg | [68] |
| Tambak lorok (Indonesia) | 6000 particles/L | [3] | Wonorejo coast (Indonesia) | 537 particles/kg | [68] |
| Kenjeraan beach (Indonesia) | 0.505 particles /L | [3] | Brisbane river (Australia) | 10–250 particles/m$^3$ | [69] |
| Fengshan river (Taiwan) | 334–1058 item/m$^3$ | [70] | Fengshan River (Taiwan) | 508–3987 item/kg | [70] |
| Dungun river (Malaysia) | 38.7–300.8 item/m$^3$ | [71] | Tebrau River (Malaysia) | 680 particles/m$^3$ | [27] |
| Austrian danube (Austria) | 141.7 particles/m$^3$ | [72] | Santubong, Kuching (Malaysia) | 0.223 g | [73] |
| Qin river (China) | 16.67–611.11 particles/m$^3$ | [74] | Trombol, Kuching (Malaysia) | 1.635 g | [73] |
| Wuhan lake (China) | 8.9 × 10$^3$ particles/m$^3$ | [22] | Skudai river (Malaysia) | 200 particles/m$^3$ | [27] |
| Shaoxing (China) | 2.1–71 particles/m$^3$ | [75] | Qin River, China | 0–97 particles/m$^3$ | [74] |
| Yellow River (China) | 479 particles/m$^3$ | [76] | Shaoxing, China | 16.7–1323.3 particles/m$^3$ | [75] |
| Han river (South Korea) | 0–42.9 particles/m$^3$ (0 m)<br>20–180 particles/m$^3$ (2 m) | [77] | | | |
| Paris (France) | 106 particles/m$^3$ | [78] | | | |

the abundance of microplastics, the amount of microplastics vary from one location to another location, season and alternation of temporal. The existence of the microplastics in freshwater systems is likely to be affected by the anthropogenic activities as the urban areas are most likely to be found to have a high percentage of microplastic particles. A study conducted in Wuhan, China with different location of river from the Wuhan City [22]. Microplastics abundance at Bei Lake and Huanzi Lake were high which were 8925 n/m$^3$ and 8550 n/m$^3$, respectively, where both of the lakes are located in the middle of Wuhan City and have the highest population density [22]. While the microplastics abundance at Wu Lake was found to be the least which was 1660 n/m$^3$ as the Wu Lake has the lowest population density and is far from the centre of Wuhan City among the lakes that being studied [22]. Not only that, the occurrence of microplastics might also cause by the development of leisure industry and lack of plastic wastes management [23]. Another research in Skudai River at Johor, Malaysia which is a famous tourist area found the quantity of microplastic are high with a microplastics abundance of 200 particles/m$^3$, where this river is well-known area for fishing and leisure activities, and was reported to have high amount of rubbish with 11 tons of rubbish collected from this river monthly due to the poor waste management [24–27].

As a function of their movement and fate, there are 2 types of MP distributions which are vertical (VD) and horizontal (HD); they are generally influenced by MP dimensions, structure, and density, as well as biota and hydrogeology [12]. According to the VD of MPs, aggregation, homo-aggregation, and hetero-aggregation are vital practices associated with MPs relocation into waterways. Aggregation is the process through which MPs interact and clump together in the water column before settling into the sediments. The volume of MPs is a significant determinant in homo-aggregation, but research on it is limited since producing homo-aggregations in aquatic systems depending on the Derjaguin—Landau—Verwey—Overbeek (DLVO) concept is challenging [12]. In fact, MPs with densities of more than 0.001 mg/cm$^3$ such as PVC and PET, can sink immediately, which is why they are commonly discovered in the freshwater sediment [12, 15]. Based on the study conducted in Korean coastal regions, PE and PP are more widely available in the surface or upper section of water bodies than PVC and PET. It is because they are able to move and transfer freely in the aqueous environment through circulation patterns due to their lower densities [28]. Algal species, chemical structure, and geometry are the characteristics that determine how MPs are hetero-aggregated in aquatic environments. MPs hetero-aggregation can also develop due to biofilm development and particle adhesion, both of which are regulated by temperature, nutrients, and colloidal matter. The creation of hetero-aggregates can also enhance the structural size of MPs, altering their destiny and dispersal activities [12].

For HD, its fundamental factors are the environmental circumstances and bio-related components distributions, which are mostly affected by hydraulic state aberrations. MPs in local freshwater zones can travel horizontally from torrents to lakes, just as they can migrate from rivers to the ocean and even to the Arctic [12, 28]. While for the bio-related dispersal, MPs are devoured by or stick to the exterior of organisms, and they may then slip off throughout biota motions. Remarkably, factors that influenced this particular distribution include the aquatic species as well as the size, geometry, and appearance of MPs. Different species have differing capabilities to transport MPs, filter-feeding fish has a higher ability to translocate MPs in aquatic creatures. MPs' volume and appearance significantly affect ingestion possibilities, as round-shaped MPs are easier to ingest and seem to marine creatures as food [12, 29].

## Potential effects of the presence of plastics

Plastics are more likely to enter the environment these days as a result of substantial manufacture and usage, and they are being discovered in every corner of the globe as shown in Table 4. The environment is gradually scrutinising plastics,

**Table 4** Summary of MP incidence in various regions of the world

| Region | Range of MPs abundance (particles/m$^3$) | Structure | References |
|---|---|---|---|
| Nakdong River Estuary, Korea | 210.00–5560.00 | PE, PP | [85] |
| Oujiang Estuary, China | 395.40–964.60 | PP, PE, PTFE, PVC | [79, 85] |
| Jiaojiang Estuary, China | 106.90–1804.30 | PP, PE, PTFE, PVC | [79, 85] |
| MinJiang Estuary, China | 714.30–1777.30 | PP, PE, PTFE, PVC | [79, 85] |
| Yangtze Estuary, China | 1675.80–6598.80 | – | [80] |
| Kuala Nerus, Malaysia | 130.00–690.00 | PA, PP | [81] |
| Kuantan Port, Malaysia | 140.00–150.00 | PS, PA, PVC, PE | [81] |
| Lamong Bay, Indonesia | 380.00–610.00 | PS, PE, PP, PET | [4] |
| Wonorejo Beach, Indonesia | 440.00–530.00 | PS, PE, PP, PET | [4] |

and global concern about ecosystem damage is expanding as the plastics can induce oxidative stress and be biomagnified throughout the food chain [25, 26, 30–33]. Researchers have also started to concentrate their efforts on terrestrial systems, after spending a long period investigating marine communities in order to truly comprehend their environmental consequences that all countries across the world confront [31, 34].

## Terrestrial plantations

MPs are being thought of as a physical pollutant in the soil, and preliminary evidence states that microfibers have resulted in soil bulk density reduction [31]. This can be further expressed as decreased root penetration opposition and improved soil ventilation, resulting in better root development. On the other hand, the presence of MPs also provides a negative influence by creating water circulation channels which can contribute to enhanced water vaporisation and soil dryness, resulting in poor plant productivity [31, 34]. Any changes in soil structure can result in various unintended consequences, and it is not easy to forecast how the alterations affect the soil's functionality. Microfibers provide an unfavourable impact on soil aggregation in this field investigation, indicating that shifts in soil structure can alter the soil aggregation process [31]. Soil aggregates are the particles that make up soil structure and determine how soil microbes live [34]. Suppose microfibers function to bind soil elements and so support the production of soil aggregates. In that case, beneficial effects on soil aggregation are also feasible, which, by altering soil structure, can have implications for soil aeration and root growth, as stated earlier [31, 34]. However, there is a chance for plastic additives to provide adverse effects on plants. Thus, future research should consider which types of MPs stimulate or restrict plant biomass synthesis [34].

## Aquatic species

MPs can be ingested by marine life via feeding, air–water interface inhalation, intake of MP-exposed animals, or direct consumption, which is considered the predominant MPs exposure pathway for marine species. There have been more than 690 documented cases of MPs being consumed by sea creatures at various spatial scales, impacting species and altering population dynamics, which are considered a severe global problem. Fish are unable to discriminate between food and MPs due to their small size, buoyancy, and appearance. After consumption, MPs in fish are traversed in the gastrointestinal region and gills before entering the cardiovascular system, where they might travel to other organs and tissues. The ingestion of MPs may cause a reduction in intestinal nutritional absorption and space available in the stomach, internal haemorrhage, hunger, and eventually an increase in mortality [30]. The majority of MPs consist of neurotoxins in their chemical constituents such as tints, plasticizers, or disinfectants that can cause more severe concerns, including behavioural abnormalities in fish, gastrointestinal distress, metabolic disorders, and genetic issues [30, 35, 36]. According to a case study conducted at the Skudai River in Malaysia, approximately 40% of fish had consumed MPs, demonstrating that MP engagement with fish species is relatively high. Besides, the majority of fish species were herbivores, indicating that MP may look like aquatic plant species. Fibres were discovered as the most abundant constituents identified in fishes' gastrointestinal systems due to their lower density and have the potential to float in the aquatic environment for a longer time [27].

Beside fish, the negative effects of polystyrene microplastics on oyster reproduction and eating were demonstrated due to changes in their food intake and energy allocation [37]. When exposed to micro-polystyrene, oysters produced fewer eggs and had lower quality of ovocytes and sperm. Oysters discharge their eggs and sperms into the water where fertilisation takes place, but because of the consumption of micro-polystyrene, fertilisation is hindered by the sperm's slower movement and lower quantity [37]. The output and growth of the oyster exposed to MPs decreased by 41 and 18%, respectively. About 40% drop in carbon biomass and lack of energy caused by polystyrene microbeads have been reported in zooplankton like copepods [38]. Copepods perish as a result of the energy shortages. Long-term exposure to MPs results in tiny eggs with fewer hatches. Affection on the immune systems and reproductive cycle were also demonstrated by shark species of the United Kingdom [39].

## Climate changes

Plastics promote a devastating legacy in the oceans, which serve as the major component of the carbon cycle. It strangles and suffocates a broad spectrum of marine species and their natural habitations, and its degradation can linger for decades or even centuries [30]. Plastics are chemically derived polymers with a basis comprised mainly of carbon bonds, and their primary constituents are obtained from fossil fuels or natural gas, both of which emit greenhouse gases [30, 32, 33]. The existence of plastics in the aquatic ecosystem contributes an adverse effect on the carbon cycle as marine flora and fauna are involved in extracting atmospheric carbon and delivering it to the ocean floor to avoid it from returning into the air. However, plastic pollution has been hampered the capability of phytoplankton to restore the atmosphere through photosynthesis. Besides, this contamination has been shown to confine the survival and reproduction rates of zooplankton, reducing carbon transmission rate to the ocean and thus affecting climate [32, 33]. Besides, sunlight and UV radiation enable plastic to generate potent greenhouse gases such as methane and ethylene, hastening climate change and creating a threatening feedback loop, as proved by Royer, Ferrón, Wilson, and Karl's study [30, 40].

## Human health effects

A study conducted by the World Health Organisation (WHO) highlighted the ubiquitous presence of MPs in the ecosystem, raising severe concerns about their introduction and potential health consequences. The pathway for MPs to assess the human system is consuming infected food and drinking water, inhalation, or cutaneous contact [41, 42]. MPs are able to pass through the intestinal system and into the systemic circulation, allowing them to reach all parts of the body. Due to their chronic structure and specific qualifiers, the associated toxicity is thought to be inflammatory, with an acquisitive effect that is dose dependent [41]. Chemical and physical effects are the main areas of MPs' effects on human health, which are further differentiated by exposure route and possible therapeutic consequences [43, 44].

### Chemical effects

Additives are the main contributors to human health impacts, which are chemicals used to strengthen plastic appearance and performance, such as watertightness, tensile strength, non-degradable and electrical resistance [41]. The majority of additives are cancer-causing agents and hormone disruptors, and different additives have varied effects and are implemented in different plastics, as seen in Table 5 [45].

### Bisphenol A (BPA)

BPA is an artificial carbon-based molecule with a faint phenolic scent that can be constructed by the combination of acetone and phenols. It is typically employed in plastics production and packaged foods due to its ability to tolerate high temperatures and pressures. These properties allow it to be used in safety devices and food products to endure heating in household appliances. BPA is also a constituent of resins in defensive varnishes, such as the interior of soft drink cans that help lengthen the preservation period of foodstuffs by inhibiting bacteria or microorganisms from interacting with the stored food. Despite its remarkable durability, the molecule's instability among plastic items enables it to leak, resulting in a high frequency of contamination in surface waters and increased human exposure [41, 46]. BPA is an inhibitory neurotransmitter that duplicates the feminine hormone oestrogen, which can cause congenital disabilities, endometriosis, and infertility. It is able to alter thyroid gland gene transcription, affecting metabolic and growth rates. Research indicates a definite connection between BPA levels in urine and liver function, heart disease, and diabetes [43]. BPA intrusion in food was blamed in 2008 for over 10,000 incidences of paediatrics obesity and 30,000 new cases of cardiovascular disease [41].

### Phthalates

The esters of phthalic acid form phthalates with two distinct length carbon branches, which are colourless and have poor reactivity and stability. Phthalates are a sort of molecules

**Table 5** Plastic additives with their corresponding health impacts and applications

| Plastic additives | Applications | Health effects | Plastic categories (*) | References |
|---|---|---|---|---|
| Bisphenol A | Packaging materials, aluminium cans, bottles | Coronary illness, reproductive abnormalities, breast cancer, hormonal disorders | PC, PVC | [41, 45, 82] |
| Phthalates | Rubber, paints, inks, synthetic perfumes, toys | Genetic mutation, allergic, psoriasis, reproductive disorders | PS, PVC | [41, 45] |
| Polychlorinated biphenyls | Electrical appliances, varnishes, lubricants, coatings | Reproductive disorders, high disease progression, hormonal issues | PVC, PC, PS, PE, PP, PTFE, PA | [45, 83] |
| Flame retardants | Textiles, electronic devices, housewares | Infertility, developmental consequences, thyroid hormone levels imbalance, prostate cancer | Polyurethane foam, PVC | [82] |
| Persistent organic pollutants | Insecticides | Growth retardation, chronic diseases, endocrine dysfunction | PVC, PC, PS, PE, PP, PTFE, PA | [41, 42] |

**PVC* Polyvinyl chloride, *PC* Polycarbonate, *PS* Polystyrene, *PE* Polyethylene, *PP* Polypropylene, *PTFE* Polytetrafluoroethylene, *PA* Polyamide that are generated in massive amounts and are the most commonly synthesised chemical. Based on the analysis, they are manufactured at a peak incidence of roughly 6 million tonnes per year, and this pace has been relatively consistent over the last 2 decades. Their main purpose is to offer plastic polymers certain features, including deformability, rigidity, and elasticity [41]. They usually can be found in the elements of raincoats, pharmaceuticals, cosmetic products, and toys [45]. They have been identified as endocrine-disrupting chemicals that can affect the human reproductive system or are carcinogenic [41, 45]. The issue is exacerbated by the fact that phthalates come in a variety of forms, each with its impact on human health, necessitating consideration of probable interactions with other additives [41]. In European Union, toys and baby care products containing phthalates in concentrations greater than 0.1% have been forbidden. Children are most susceptible to phthalates through their frequent mouthing of objects like hands frequently in contact with plastic toys or baby bottles [41, 45].

### Physical effects

The proportion of airborne MPs is increasing over the world, with synthetics fabrics and dust accounting for the vast bulk of atmospheric MPs. Fibres can be sourced from daily wear or laundry; one piece of clothing can free up to 2000 fibres after being washed. MPs particles were discovered in the dust in Tehran and Iran, with 11.55 and 60 particles per gram of dust, respectively. Although the high percentage of fibres is considered to be eliminated from the airways, the remainder has the potential to induce inflammatory reactions and pulmonary infections, particularly in people with defective clearance systems. Plastics fibres were detected in over 85% of lung tissues from people having lung tumour excision, indicating that the microscopic fibres cannot be removed during exhalation and thus accumulate in lung tissue. Other contaminants behave as reactive oxygen species and are inhaled daily by humans, causing oxidative stress, tissue damage, and tumorigenesis, which raises respiratory illness risk and lung cancer in persons exposed to a lower concentration of plastic fibres [43]. Besides, considering the high seafood consumption around the world, human exposure to MPs is unavoidable [43, 44]. An examination of the quantity of MPs consumed from the average daily diet revealed that the regular consumption was 45,500 particles per year [43]. In fact, humans can excrete more than 90% of ingested MPs through faeces, while the rest remain in the body due to their bigger size, form, and composition. The physical impacts of accumulated MPs in human bodies include enhanced infectious agents, adsorbed toxic compounds, and interruption of intestinal microbiota. MPs can travel through the cell membrane and concentrate in other body parts, causing the immune system to be harmed even more. They are also able to get through the blood–brain boundary and into the digestive and respiratory systems, where they could cause considerable injury due to their diminished size and large specific surface area [44].

## Remediation technologies for MP removal

The presence of MP in the water resources has increased significantly in our lives in recent years, posing serious health risks to living species and humans, as stated previously. As a result, effective and reliable technologies must be employed to eliminate MPs from the water supplies in order to provide better quality for the living organisms. A variety of remediation strategies, including physically, chemically, or biologically, can be achieved to remove MP from water resources, as illustrated in Table 6.

### Electrocoagulation (EC)

Coagulants are formed in the EC process by interacting with metallic ions such as ferrous ($Fe^{2+}$) and aluminium ($Al^{3+}$) ions, which are relieved from anode and cathode through electrolysis, together with hydroxyl ($OH^-$) ions from the solution. The coagulants then disintegrate the colloidal by neutralising the charges on the suspended MPs' surfaces, allowing them to engage via interaction forces [47, 48]. Simultaneously, the coagulant builds a slurry layer to capture MPs in contaminated water. Hydrogen gas is released throughout the process to drive the resulting slurry to the solution's surface [48]. Based on the research, the EC procedure can remove up to 99% of MPs under the slightly alkaline conditions of a pH of 7.5 and a sodium chloride (NaCl) solution concentration of 0 to 2000 mg/L [47]. It is a simple yet cost-effective technique by simply using metal electrodes throughout the operation [48]. However, electrodes must be serviced or changed on a frequent basis since they are subjected to higher pressures during the coagulation process to transmit electricity into the fluid, resulting in mechanical damage. Besides, they are highly dependent on electricity, requiring DC power to operate [47].

### Magnetic extraction (ME)

ME is a separation methodology that enables magnetic nanoparticles and acidic solution along with a magnetic field to speed up the extraction process [32, 33]. Iron-based nanoparticles are commonly used in this technique because of their economic price, large surface area to volume ratio, and high magnetism vulnerability. Iron nanoparticles are layered with water insulators to render them hydrophobic, allowing MPs to be magnetically retrieved from the water. ME has been demonstrated to be more effective at removing small

**Table 6** Remediation methods with their pros and cons

| Methods | Roles | Advantages | Disadvantages | References |
|---|---|---|---|---|
| Electrocoagulation | Coagulants are formed utilising metal electrodes and an electrical source | High efficiency<br>Low operating costs<br>Automated systems<br>Able to remove tiny particles | High chemicals consumption<br>High consumption of electrodes replacement<br>Electricity reliant | [32, 33, 47] |
| Membrane filtration | MPs are trapped by allowing the contaminated water to pass through the film | Simple operation<br>Low operating cost<br>No chemical is required | Membrane clogging<br>Regular maintenance needed | [32, 33, 47] |
| Biological degradation | MPs are degraded into other chemical compounds ($CH_4$, $H_2S$, $CO_2$, $H_2O$) | Low operating cost<br>Environmental friendly<br>Low energy required | Long period of time needed<br>Low efficiency<br>Environmental conditions are unpredictable | [32, 33, 47, 84] |
| Magnetic extraction | MPs are separated using magnetic particles, acid, and magnetism | Low operation cost<br>Able to remove tiny-sized MP | Secondary MP generated that cause pollution | [47] |
| Photocatalytic degradation | Decompose MPs into water and carbon dioxide | No chemicals are needed<br>Ecologically sustainable<br>Less energy required | Low removal efficiency<br>Secondary MP generated that cause contamination | [47] |

MP (<0.02 mm), with MPs recovered from the ocean at a rate of more than 90%. While only 84% and 78% of medium MPs (0.2–1 mm) are recovered from freshwater and river beds, correspondingly due to their smaller specific surface area [32, 33, 49]. The recovery percentage in the river bed is poorer due to soil particles obstruct nanoparticles from interacting with plastic and bioactive compounds [50]. As a result, it has been suggested that this technology is better suited for drinking water purification [32, 33, 49, 50]. On the other hand, nanoparticles utilised cannot be reused or disposed of, leading to secondary pollution [50–52].

## Membrane filtration

Membrane filtration is frequently implemented in drinking water treatment because of its consistent removal efficiency and ease of application. Membranes have high selectivity and removal efficiency, allowing them to extract biological contaminants, multi-charged ions, and disinfectants while simultaneously lowering water hardness. Membranes are functioned as borders to separate MPs from treated water [32, 33]. Membrane fouling is a common occurrence in this process, resulting in a reduction in permeability and flow velocity; hence, regular washing or pre-treatment is highly necessitated [49]. It can be managed using effective intervention like coagulation, which is a popular pre-treatment step for promoting MPs flocculation. MPs are susceptible to clumping due to their characteristics; however, the agglomeration is instability and readily fragmented, requiring the introduction of coagulants to form a more robust structure for simpler extraction [32, 33].

## Biological degradation

Biodegradation is characterised as the potential of microbes to break down substances through physiochemical or enzymatic activities [53–58]. Bacteria are the most abundant of all microorganisms and are widely known for their capacity to degrade pollutants; nevertheless, they are notorious for consuming a long time, frequently up to 3 months. Bacteria decompose polymers into shorter sections or fragments that can pass through their membrane. The complete decomposition of a polymer yields $CH_4$, $H_2S$, $CO_2$, and $H_2O$, using a source of energy. The process is influenced by environmental factors such as temperature, alkalinity or acidity, and ultraviolet radiation. In future investigations, it will be critical to standardise settings and enhance genotypes of microbe in order to speed up the degradation practice of MPs [59]. However, it is simple to operate and environmentally beneficial, as it does not involve chemicals or additives in the process. However, a long retention time is required and difficult to scale up [49].

## Photocatalysis

Photocatalysis is a combination of reduction and oxidation processes, in which a semiconductor absorbs sufficient photons to transport electrons from the valence band to the conduction band while leaving positive charges behind. The motivated ions have subsequently interacted with water, hydroxide ion, or oxygen in the environment to form reactive oxidants like superoxide anion, which commences the plastic destruction practice by disrupting the chain, splitting, and eventually decomposing into water and carbon dioxide [60, 61]. Zinc oxide is the most extensively used photocatalyst due to its superior optical characteristics, ionic conductivity, and chemical inertness. Furthermore, it is simple to be manufactured and shaped into various forms under simple chemical water bath techniques [61]. This remediation practice is economical as it does not involve using any additives or electricity, and it does not release hazardous substances into the surroundings [49, 60]. However, it has a lower removal efficiency when compared to other remediation technologies and requires a more extended retention duration [49].

## Challenges faced on studies

Retrieving safe drinking water has become problematic as MPs can reach drinking water supplies from a variety of sources, including WWTPs, industrialised sludge, and disintegrated plastic litter [62]. Regardless of the reality that many analyses have been conducted on the abundance of MPs, our comprehension of the MP remains restricted [63]. Therefore, researchers should place their attention on broadening the geographical scope of the investigation to encompass not only terrestrial but also aquatic habitats [16, 17]. Scientific appliances must also be improved, as the absence of standardised methodologies for ecological samples makes it impossible to identify MPs reliably. It can be defined that the scientific data sample collection, extraction, and detection all are time-consuming, posing a significant barrier to sizable assessment. The most commonly used MPs detection technique are microscopy, Fourier Transform Infra-Red (FTIR), Raman spectroscopy and thermal analysis. This techniques have shown some success in the detecting plastics when it used individually or combination of two techniques. FTIR and Raman spectroscopy techniques ensure more reliable results since they have a vibrational complementarity. However, the effectiveness of MP detection is influenced by numerous circumstances. In some case for instance, plastic additives made it challenging to identify fundamental polymers requiring spectrum subtraction or database analysis to identify and acknowledge them correctly. MPs are widespread in nature; hence, it is challenging to quantify MP pollution without causing intervention. The implementation of practical classification approaches will allow for a more realistic depiction of the MP areal extent in aquatic settings, as well as increased comparability within research findings, thus it is crucial to use the appropriate detection techniques [63].

Although various remediation technologies exist to remove MPs from the water resources, their effectiveness is insufficient to keep MPs at water treatment plants. Despite the fact that many studies have concentrated on establishing the existence of MPs in the wastewater stream, the MP removal mechanisms in each stage of the facility are incompletely understood [64]. The wastewater analysis is imperative as it is the primary cause of MP in available water resources, which reduces their sustainability for human consumption [62]. Even though MPs are achieved to significant levels of clearance, as investigated in the prior study, negligible by-products would be discharged into watercourses, further degrading the ecosystem [64]. Besides, effective technologies can be costly and complicated to integrate into existing plants, so they are only employed when necessary [62, 64]. Notwithstanding our concerns about MP biotoxicity, we need to keep in mind that our knowledge of the deleterious effects of MP pollution on biodiversity or food protection and security is still limited [63]. As a result, more action must be taken to reduce the global spread of MP contamination. The most crucial factor is that nations must be united and work in the same direction to deal with this situation as the majority of countries have yet to introduce a framework to address the principal contributors of MPs accumulating in the water bodies or successfully managing their relevant aspects [64]. Many countries have implemented reduction and recycling initiatives to raise public awareness about plastics; however, much more improvement is needed. It is because public attention is sometimes transient, and it is necessary to imprint in their thoughts. A balance must be struck between picking the correct decision and making the simplest or commercially sustainable one [5]. Communities are considered the main stakeholders in handling MP pollution since their cooperation with authorities is highly appreciated in tackling this problem [62].

## Conclusion

Plastics are undeniably advantageous for society, but they have turned into an environmental menace, as evidenced by areas with abnormally high concentrations of plastics, especially for MPs. MPs can travel a long distance from their point of origin by wind or water, causing the environmental impact to be more significant than expected. Environmental MPs have a negative impact on land species, causing the extinction of certain species and impeding plantation growth, as well as contributing to climate change. Humans are mainly exposed to MPs via ingesting or drinking, which accumulate in their bodies and constitute a human risk. Due to their fractured form, tiny size, and a wide variety of probable origins, key issues derived from the concept of pinpointing the specific source of the MPs. Therefore, monitoring processes serve an significant role in the mitigation and control of MP pollution as the fate of MPs can be fully identified. Effective strategies or treatments must be introduced to cut down the amount of MPs being discharged in order to preserve natural systems and sustain the quality standards for domestic purposes. As a result, the usage and release of MPs can be severely constrained by enacting comprehensive legislation to regulate plastics use or MP release as part of a worldwide strategy, even before the results of long-term assessments are available.

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### Declaration

**Conflict of interest** The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported.

## References

1. Thompson RC, Moore CJ, Vom Saal FS, Swan SH (2009) Plastics, the environment and human health: current consensus and future trends. Philos Trans R Soc B Biol Sci 364(1526):2153–2166. 10.1098%2Frstb.2009.0053
2. Klöckner P, Reemtsma T, Wagner S (2021) The diverse metal composition of plastic items and its implications. Sci Tot Environ. https://doi.org/10.1016/j.scitotenv.2020.142870
3. Cordova MR, Purwiyanto AIS, Suteja Y (2019) Abundance and characteristics of microplastics in the northern coastal waters of Surabaya, Indonesia. Mar Pollut Bull 142:183–188. https://doi.org/10.1016/j.marpolbul.2019.03.040
4. Curren E, Kuwahara VS, Yoshida T, Leong SCY (2021) Marine microplastics in the ASEAN region: a review of the current state of knowledge. Environ Pollut. https://doi.org/10.1016/j.envpol.2021.117776
5. Horton AA, Barnes DK (2020) Microplastic pollution in a rapidly changing world: implications for remote and vulnerable marine ecosystems. Sci Tot Environ. https://doi.org/10.1016/j.scitotenv.2020.140349
6. Jambeck JR, Geyer R, Wilcox C, Siegler T, Perryman M, Andrady A, Narayan R, Law KL (2015) Plastic waste inputs from land into the ocean. Sci 347(6223):768–771. https://doi.org/10.1126/science.1260352
7. Danopoulos E, Twiddy M, Rotchell JM (2020) Microplastic contamination of drinking water: a systematic review. PLoS ONE. https://doi.org/10.1371/journal.pone.0236838
8. Boucher J, Friot D (2017) Primary microplastics in the oceans: a global evaluation of sources (Vol. 10). Gland, Switzerland: IUCN Report. https://holdnorgerent.no/wp-content/uploads/2020/03/IUCN-report-Primary-microplastics-in-the-oceans.pdf. Accessed 10 Apr 2021
9. Jaikumar G, Brun NR, Vijver MG, Bosker T (2019) Reproductive toxicity of primary and secondary microplastics to three cladocerans during chronic exposure. Environ Pollut 249:638–646. https://doi.org/10.1016/j.envpol.2019.03.085
10. Webb HK, Arnott J, Crawford RJ, Ivanova EP (2013) Plastic degradation and its environmental implications with special reference to poly (ethylene terephthalate). Polymers 5(1):1–18. https://doi.org/10.3390/polym5010001
11. Anderson AG, Grose J, Pahl S, Thompson RC, Wyles KJ (2016) Microplastics in personal care products: exploring perceptions of environmentalists, beauticians and students. Mar Pollut Bull 113(1–2):454–460. https://doi.org/10.1016/j.marpolbul.2016.10.048
12. Ding R, Tong L, Zhang W (2021) Microplastics in freshwater environments: sources, fates and toxicity. Water Air Soil Pollut 232(5):1–19. https://doi.org/10.1007/s11270-021-05081-8
13. Fortin S, Song B, Burbage C (2019) Quantifying and identifying microplastics in the effluent of advanced wastewater treatment systems using Raman microspectroscopy. Mar Pollut Bull 149:110579. https://doi.org/10.1016/j.marpolbul.2019.110579
14. Ngo PL, Pramanik BK, Shah K, Roychand R (2019) Pathway, classification and removal efficiency of microplastics in wastewater treatment plants. Environ Pollut 255(2):113326. https://doi.org/10.1016/j.envpol.2019.113326
15. Carr SA, Liu J, Tesoro AG (2016) Transport and fate of microplastic particles in wastewater treatment plants. Water Res 91:174–182. https://doi.org/10.1016/j.watres.2016.01.002
16. Meng F, Fan T, Yang X, Riksen M, Xu M, Geissen V (2020) Effects of plastic mulching on the accumulation and distribution of macro and micro plastics in soils of two farming systems in Northwest China. Peer J. https://doi.org/10.7717/peerj.10375
17. Meng Y, Kelly FJ, Wright SL (2020) Advances and challenges of microplastic pollution in freshwater ecosystems: a UK perspective. Environ Pollut. https://doi.org/10.1016/j.envpol.2019.113445
18. Zhou A, Zhang Y, Xie S, Chen Y, Li X, Wang J, Zou J (2021) Microplastics and their potential effects on the aquaculture systems: a critical review. Rev Aquac 13(1):719–733. https://doi.org/10.1111/raq.12496
19. Almroth BMC, Åström L, Roslund S, Petersson H, Johansson M, Persson NK (2018) Quantifying shedding of synthetic fibers from textiles; a source of microplastics released into the environment. Environ Sci Pollut Res 25(2):1191–1199. https://doi.org/10.1007/s11356-017-0528-7
20. De Falco F, Di Pace E, Cocca M, Avella M (2019) The contribution of washing processes of synthetic clothes to microplastic pollution. Sci Rep 9(1):1–11. https://doi.org/10.1038/s41598-019-43023-x
21. Petersen F, Hubbart JA (2020) The occurrence and transport of microplastics: the state of the science. Sci Tot Environ. https://doi.org/10.1016/j.scitotenv.2020.143936
22. Wang W, Ndungu AW, Li Z, Wang J (2017) Microplastics pollution in inland freshwaters of China: a case study in urban surface waters of Wuhan, China. Sci Tot Environ 575:1369–1374. https://doi.org/10.1016/j.scitotenv.2016.09.213
23. Lee BXY, Ponraj M, Widyasamratri H, Wang J (2021) Green building practices on waste minimization in China construction

industry. Ind Domest Waste Manage 1(1):12–25. https://doi.org/10.53623/idwm.v1i1.36

24. Liew ZR, Monir MU, Kristanti RA (2021) Scenario of municipal waste management in Malaysia. Ind Domest Waste Manage 1(1):41–47. https://doi.org/10.53623/idwm.v1i1.50
25. Tang KHD (2021) Interactions of microplastics with persistent organic pollutants and the ecotoxicological effects: a review. Trop Aqua Soil Pollut 1(1):24–34. https://doi.org/10.53623/tasp.v1i1.11
26. Tang YY, Tang KHD, Maharjan AK, Aziz AA, Bunrith S (2021) Malaysia moving towards a sustainability municipal waste management. Ind Domest Waste Manage (1):26-40. https://doi.org/10.53623/idwm.v1i1.51
27. Sarijan S, Azman S, Mohd Said MI, Lee, MH (2019) Ingestion of Microplastics by Commercial Fish in Skudai River, Malaysia. Environ Asia 12(3):75–84. https://doi.org/10.14456/ea.2019.47
28. Song YK, Hong SH, Eo S, Jang M, Han GM, Isobe A, Shim WJ (2018) Horizontal and vertical distribution of microplastics in Korean coastal waters. Environ Sci Technol 52(21):12188–12197. https://doi.org/10.1021/acs.est.8b04032
29. Obbard RW (2018) Microplastics in polar regions: the role of long range transport. Curr Opin Environ Sci Health 1:24–29. https://doi.org/10.1016/j.coesh.2017.10.004
30. Kumar S, Rajesh M, Rajesh KM, Suyani NK, Rasheeq Ahamed A, Pratiksha KS (2020) Impact of microplastics on aquatic organisms and human health: a review. Int J Environ Sci Nat Resour 26(2):59–64. https://doi.org/10.19080/IJESNR.2020.26.556185
31. Rillig MC, Lehmann A, de Souza Machado AA, Yang G (2019) Microplastic effects on plants. New Phytol 223(3):1066–1070. https://doi.org/10.1111/nph.15794
32. Shen M, Huang W, Chen M, Song B, Zeng G, Zhang Y (2020) (Micro) plastic crisis: un-ignorable contribution to global greenhouse gas emissions and climate change. J Clean Prod. https://doi.org/10.1016/j.jclepro.2020.120138
33. Shen M, Song B, Zhu Y, Zeng G, Zhang Y, Yang Y, Wen X, Chen M, Yi H (2020) Removal of microplastics via drinking water treatment: current knowledge and future directions. Chemosphere. https://doi.org/10.1016/j.chemosphere.2020.126612
34. Rillig MC, Lehmann A (2020) Microplastic in terrestrial ecosystems. Science 368(6498):1430–1431. 10.1126%2Fscience.abb5979
35. Andreas, Hadibarata T, Sathishkumar P, Prasetia H, Hikmat, Pusfitasari ED, Tasfiyati AN, Muzdalifah D, Waluyo J, Randy A, Ramadhaningtyas DP, Zuas O, Sari AA (2021) Microplastic contamination in the Skipjack Tuna (*Euthynnus affinis*) collected from Southern Coast of Java Indonesia. Chemosphere 276:130185 https://doi.org/10.1016/j.chemosphere.2021.130185
36. Clark JR, Cole M, Lindeque PK, Fileman E, Blackford J, Lewis C, Lenton TM, Galloway TS (2016) Marine microplastic debris: a targeted plan for understanding and quantifying interactions with marine life. Front Ecol Environ 14(6):317–324. https://doi.org/10.1002/fee.1297
37. Sussarellu R, Suquet M, Thomas Y, Lambert C, Fabioux C, Pernet MEJ, Le Goic N, Quillie V, Mingant C, Epelboin Y, Corporeau C, Guyomarch J, Robbens J, Paul-Pont I, Soudant P, Huvet A (2016) Oyster reproduction is affected by exposure to polystyrene microplastics. Proc Natl Acad Sci 113:2430–2435. https://doi.org/10.1073/pnas.1519019113
38. Cole M, Lindeque P, Fileman E, Halsband C, Galloway TS (2015) The impact of polystyrene microplastics on feeding, function and fecundity in the marine copepod *Calanus helgolandicus*. Environ Sci Technol 49:1130–1137. https://doi.org/10.1021/es504525u
39. Parton KJ, Godley BJ, Santillo D, Tausif M, Omeyer LCM, Galloway TS (2020) Investigating the presence of microplastics in demersal sharks of the North-East Atlantic. Sci Rep 10:12204. https://doi.org/10.1038/s41598-020-68680-1
40. Royer SJ, Ferrón S, Wilson ST, Karl DM (2018) Production of methane and ethylene from plastic in the environment. PLoS ONE 13(8):e0200574. https://doi.org/10.1371/journal.pone.0200574
41. Campanale C, Massarelli C, Savino I, Locaputo V, Uricchio VF (2020) A detailed review study on potential effects of microplastics and additives of concern on human health. Int J Environ Res Public Health 17(4):1212. https://doi.org/10.3390/ijerph17041212
42. Rahman A, Sarkar A, Yadav OP, Achari G, Slobodnik J (2020) Potential human health risks due to environmental exposure to microplastics and knowledge gaps: a scoping review. Sci Tot Environ. https://doi.org/10.1016/j.scitotenv.2020.143872
43. Blackburn K, Green D (2021) The potential effects of microplastics on human health: what is known and what is unknown. Ambio 51:518–530. https://doi.org/10.1007/s13280-021-01589-9
44. Smith M, Love DC, Rochman CM, Neff RA (2018) Microplastics in seafood and the implications for human health. Curr Environ Health Rep 5(3):375–386. 10.1007%2Fs40572-018-0206-z
45. Alabi OA, Ologbonjaye KI, Awosolu O, Alalade OE (2019) Public and environmental health effects of plastic wastes disposal: a review. J Toxicol Risk Assess 5:021. https://doi.org/10.23937/2572-4061.1510021
46. Zahari AM, Shuo CW, Sathishkumar P, Yusoff ARM, Gu FL, Buang NA, Lau W-J, Gohari RJ, Yusop Z (2018) A reusable electrospun PVDF-PVP-MnO2 nanocomposite membrane for bisphenol A removal from drinking water. J Environ Chem Eng 6(5):5801–5811. https://doi.org/10.1016/j.jece.2018.08.073
47. Padervand M, Lichtfouse E, Robert D, Wang C (2020) Removal of microplastics from the environment. A review. Environ Chem Lett 18(3):807–828. https://doi.org/10.1007/s10311-020-00983-1
48. Perren W, Wojtasik A, Cai Q (2018) Removal of microbeads from wastewater using electrocoagulation. AC Omega 3(3):3357–3364. https://doi.org/10.1021/acsomega.7b02037
49. Dey TK, Uddin ME, Jamal M (2021) Detection and removal of microplastics in wastewater: evolution and impact. Environ Sci Pollut Res 28:1–23. https://doi.org/10.1007/s11356-021-12943-5
50. Grbic J, Nguyen B, Guo E, You JB, Sinton D, Rochman CM (2019) Magnetic extraction of microplastics from environmental samples. Environ Sci Technol Lett 6(2):68–72. https://doi.org/10.1021/acs.estlett.8b00671
51. Chung JH, Hasyimah N, Hussein N (2022) Application of carbon nanotubes for remediation of emerging pollutants. A review. Trop Aqua Soil Pollut 2(1):13–26. https://doi.org/10.53623/tasp.v2i1.27
52. Kristanti RA, Liong RMY, Hadibarata T (2021) Soil remediation applications of Nanotechnology. Trop Aqua Soil Pollut 1(1):35–45. https://doi.org/10.53623/tasp.v1i1.12
53. Devi RS, Kannan VR, Natarajan K, Nivas D, Kannan K, Chandru S, Antony AR (2016) The role of microbes in plastic degradation. In: Saxena, G, Bharagava RN (Ed.), Environ Waste Manage 341–370. CRC Press. https://doi.org/10.1201/b19243-13
54. Kristanti RA, Hadibarata T, Al Farraj DA, Elshikh MS, Alkufeidy RM (2018). Biodegradation mechanism of phenanthrene by halophilic *Hortaea sp*. B15. Water Air Soil Pollut 229:324. https://doi.org/10.1007/s11270-018-3969-9
55. Zainip VJ, Adnan LA, Elshikh MS (2021) Decolorization of remazol brilliant violet 5R and procion red MX-5B by Trichoderma species. Trop Aqua Soil Pollut 1(2):108–117
56. Hadibarata T, Kristanti RA (2014) Fluorene biodegradation and identification of transformation products by white-rot fungus armillaria sp. F022. Biodegradation 25(3):373–382. https://doi.org/10.1007/s10532-013-9666-x
57. Hadibarata T, Yusoff ARM, Kristanti RA (2012) Acceleration of anthraquinone-type dye removal by white-rot fungus under

optimized environmental conditions. Water Air Soil Pollut 223(8):4669–4677. https://doi.org/10.1007/s11270-012-1177-6

58. Kristanti RA, Kanbe M, Toyama T, Tanaka Y, Tang Y, Wu X, Mori K (2012) Accelerated biodegradation of nitrophenols in the rhizosphere of *Spirodela polyrrhiza*. J Environ Sci 24(5):800–807. https://doi.org/10.1016/S1001-0742(11)60839-5
59. Yuan J, Ma J, Sun Y, Zhou T, Zhao Y, Yu F (2020) Microbial degradation and other environmental aspects of microplastics/plastics. Sci Tot Environ. https://doi.org/10.1016/j.scitotenv.2020.136968
60. Ouyang Z, Yang Y, Zhang C, Zhu S, Qin L, Wang W, He D, Zhou Y, Luo H, Qin F (2021) Recent advances in photocatalytic degradation of plastics and plastic-derived chemicals. J Mater Chem A 9:13402–13441. https://doi.org/10.1039/D0TA12465F
61. Tofa TS, Kunjali KL, Paul S, Dutta J (2019) Visible light photocatalytic degradation of microplastic residues with zinc oxide nanorods. Environ Chem Lett 17(3):1341–1346. https://doi.org/10.1007/s10311-019-00859-z
62. Aljaradin M (2020) Biodegradation of microplastics in drinking water, a review. Sustain Resour Manage J 5(1):1–17. https://doi.org/10.5281/zenodo.4454872
63. Yu Y, Zhou D, Li Z, Zhu C (2018) Advancement and challenges of microplastic pollution in the aquatic environment: a review. Water Air Soil Pollut 229:140. https://doi.org/10.1007/s11270-018-3788-z
64. Westphalen H, Abdelrasoul A (2018) Challenges and treatment of microplastics in water. In M. Glavan (Ed.), Water Challenges of an Urbanizing World 5:71–82. IntechOpen. https://doi.org/10.5772/intechopen.71494
65. Guo J, Li X, Guo Y, Ruan J, Qiao Q, Zhang J, Bi Y, Li F (2016) Research on flotation technique of separating PET from plastic packaging wastes. Procedia Environ Sci 31:178–184. https://doi.org/10.1016/j.proenv.2016.02.024
66. Law KL, Starr N, Siegler TR, Jambeck JR, Mallos NJ, Leonard GH (2020) The United States' contribution of plastic waste to land and ocean. Sci Adv 6(44):eabd0288. https://doi.org/10.1126/sciadv.abd0288.
67. Chen HL, Nath TK, Chong S, Foo V, Gibbins C, Lechner AM (2021) The plastic waste problem in Malaysia: management, recycling and disposal of local and global plastic waste. SN Appl Sci 3(4):1–15. https://doi.org/10.1007/s42452-021-04234-y
68. Firdaus M, Trihadiningrum Y, Lestari P (2020) Microplastic pollution in the sediment of Jagir Estuary, Surabaya City. Indonesia Mar Pollut Bull 150:110790. https://doi.org/10.1016/j.marpolbul.2019.110790
69. He B, Goonetilleke A, Ayoko GA, Rintoul L (2020) Abundance, distribution patterns, and identification of microplastics in Brisbane River sediments. Australia Sci Tot Environ 700:134467. https://doi.org/10.1016/j.scitotenv.2019.134467
70. Tien C, Wang Z, Chen CS (2020) Microplastics in water, sediment and fish from the Fengshan River system: relationship to aquatic factors and accumulation of polycyclic aromatic hydrocarbons by fish. Environ Pollut 265:114962. https://doi.org/10.1016/j.envpol.2020.114962
71. Hwi TY, Ibrahim YS, Khalik WMAWM (2020) Microplastic abundance, distribution, and composition in Sungai Dungun, Terengganu, Malaysia. Sains Malays 49(7):1479–1490. https://doi.org/10.17576/jsm-2020-4907-01.
72. Lechner A, Keckeis H, Lumesberger-Loisl F, Zens B, Krusuch R, Tritthart M, Glas M, Schludermann E (2014) The Danube so colourful: a potpourri of plastic litter outnumbers fish larvae in Europe's second largest river. Environ Pollut 188:177–181. https://doi.org/10.1016/j.envpol.2014.02.006
73. Noik VJ, Tuah PM (2015) A first survey on the abundance of plastics fragments and particles on two sandy beaches in Kuching, Sarawak, Malaysia. IOP Conf Ser: Mater Sci Eng. https://doi.org/10.1088/1757-899X/78/1/012035
74. Zhang L, Liu J, Xie Y, Zhong S, Yang B, Lu D, Zhong Q (2020) Distribution of microplastics in surface water and sediments of Qin river in Beibu Gulf. China Sci Tot Environ. https://doi.org/10.1016/j.scitotenv.2019.135176
75. Deng H, Wei R, Luo W, Hu L, Li B, Di Y, Shi H (2020) Microplastic pollution in water and sediment in a textile industrial area. Environ Pollut. https://doi.org/10.1016/j.envpol.2019.113658
76. Han M, Niu X, Tng M, Zhang B, Wang G, Yue W, Kong X, Zhu J (2020) Distribution of microplastics in surface water of the lower Yellow River near estuary. Sci Tot Environ. https://doi.org/10.1016/j.scitotenv.2019.135601
77. Park T, Lee S, Lee M, Lee J, Le S, Zoh K (2020) Occurrence of microplastics in the Han River and riverine fish in South Korea. Sci Tot Environ. https://doi.org/10.1016/j.scitotenv.2019.134535
78. Dris R, Gasperi J, Rocher V, Saad M, Renault N, Tassin B (2015) Microplastic contamination in an urban area: a case study in Greater Paris. Environ Chem 12(5): 592–599. https://hal-enpc.archives-ouvertes.fr/hal-01134553/file/dris2015.pdf.
79. Zhao S, Zhu L, Li D (2015) Microplastic in three urban estuaries, China. Environ Pollut 206:597–604. https://doi.org/10.1016/j.envpol.2015.08.027
80. Zhao S, Zhu L, Wang T, Li D (2014) Suspended microplastics in the surface water of the Yangtze Estuary System, China: first observations on occurrence, distribution. Mar Pollut Bull 86(1–2):562–568. https://doi.org/10.1016/j.marpolbul.2014.06.032
81. Khalik WMAWM, Ibrahim YS, Anuar ST, Govindasamy S, Baharuddin NF (2018) Microplastics analysis in Malaysian marine waters: a field study of Kuala Nerus and Kuantan. Mar Pollut Bull 135:451–457. https://doi.org/10.1016/j.marpolbul.2018.07.052
82. Meeker JD, Sathyanarayana S, Swan SH (2009) Phthalates and other additives in plastics: human exposure and associated health outcomes. Phil Transactions R Soc B:Biol Sci 364(1526):2097–2113. 10.1098%2Frstb.2008.0268
83. Erickson MD, Kaley RG (2011) Applications of polychlorinated biphenyls. Environ Sci Pollut Res 18(2):135–151. https://doi.org/10.1007/s11356-010-0392-1
84. Hu K, Tian W, Yang Y, Nie G, Zhou P, Wang Y, Duan X, Wang S (2021) Microplastics remediation in aqueous systems: Strategies and technologies. Water Res. https://doi.org/10.1016/j.watres.2021.117144
85. Hamid FS, Bhatti MS, Anuar, N, Anuar N, Mohan P, Periathamby A (2018) Worldwide distribution and abundance of microplastic: how dire is the situation? Waste Manage Res 36(10): 873–897. 10.1177%2F0734242X18785730