

Microplastic in the environment: identification, occurrence, and mitigation measures

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ABSTRACT

Microplastic is an emerging pollutant causing trouble worldwide due to its extensive distribution and potential hazards to the ecological system. Some fundamental questions about microplastics, such as their presence, source, and possible hazards, remain unanswered. These issues develop because of a lack of systematic and comprehensive microplastic analysis. As a result, we thoroughly evaluated current knowledge on microplastics, including detection, characterization, occurrence, source, and potential harm. Microplastics are found in seawater, soil, wetlands, and air matrices worldwide based on findings. Visual classification, which can be enhanced by combining it with additional tools, is one of the most used methods for identifying microplastics. As soon as is practicable, microplastics analytical methods ought to be standardized. New techniques for analyzing nano-plastics are urgently needed in the meantime. Numerous studies have shown that microplastics' impacts on people and soil are significantly influenced by their size, shape, and surface physicochemical characteristics. Finally, this study suggests areas for future research based on the knowledge gaps in the area of microplastics.

Keywords: Microplastics; Identification methods; Occurrence; Potential risk; Mitigation measures

1. Introduction

Due to unique properties such as corrosion resistance, lightweight, low cost, and stable chemical properties, plastic has been intensively used in medicine, agriculture, and

industry since it was invented in 1907 [1,2]. Plastic is formed by polycondensation, or polymerization reaction of a raw material called monomer. The plastic deformation resistance is moderate between rubber and fiber. Although plastics have brought many benefits to humans, it generates much

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waste for the environment. Today, 300 million tons of plastic waste are produced every year. That's nearly equivalent to the weight of the entire human population [3–5].

Plastics have become a symbol of the inherited single-use consumption culture since they offer convenient, light, and inexpensive alternatives to everyday activities. Despite growing awareness of plastics' inescapable environmental and health risks, millions of tons are produced each year [6,7]. Plastic materials are synthetic or semi-synthetic organic polymers produced by polymerizing monomers derived from oil, natural gas, or coal [8]. Plastics are gradually broken down into smaller particles in the natural aquatic and terrestrial settings. Over the last decade, the focus has changed from macro-plastics to microplastics and nano-plastics [9,10].

Microplastics, which range from 0.1 to 1,000 μm , are among the most dangerous plastic fragments or particles in aquatic ecosystems [11]. Microplastics are divided into primary and secondary microplastics based on their size, origin, and chemical composition. Primary microplastics are manufactured in the form of plastic-based fragments or pellets, which can be found as nurdles (tiny plastic pellets ranging from 0.1 to 1,000 μm) in a variety of industrial facilities, microfibers (0.1–1,000 μm) in textiles, and microbeads (1–1,000 μm) in cosmetics [12]. Physical and chemical aging and degradation of microplastics such as disposable dishes, plastic bags, fishing nets, computer casings, plastic bottles, and foam goods produce secondary microplastics. Car tires (56%), painting and maintenance of ships, recreational boats, buildings, constructions, and roads (24%), and loss from plastic production (10%) are some of the sources of microplastics in the natural environment [13].

Following the rise of unanswered questions about the degradability and toxicity of microplastics, as well as the associated problem of plastic litter accretion in the oceans, the scientific community, and the media have been focusing on the accumulation of these non-visible plastics in the aquatic environment [13]. Although wastewater treatment facilities (WWTPs) can remove >90% of large microplastics, the removal effectiveness of small microplastics (500 μm) and the nanoplastics are extremely poor. Besides, 65 million microplastics are released into clean water resources per day [14]. As a result, microplastic discharged from WWTPs into surface waters endangers aquatic life and human health. Furthermore, most microplastics have hydrophobic surfaces and an abundance of functional groups, which interact with several different substances in the aquatic environment, including organic and inorganic pollutants, particularly those with a hydrophobic character and poor solubility [15]. Biofilms on the surface of microplastics can be colonized by various microorganisms, including bacteria and microalgae. Understanding the sorption and interactions between microplastics and pollutants is thus a critical component of investigating microplastics' effects on water [16].

Microplastics' effects on aquatic systems were of little concern in the early 1970s, but they have been revived in recent decades [17]. According to a recent bibliometric survey, more than 3,000 peer-reviewed research articles have reported microplastics' environmental consequences, fate, toxicity, and the sorption of pollutants on microplastic under diverse environmental circumstances [12,18]. Hundreds of

review articles on microplastics have been published in the last decade, covering a wide range of topics, including (i) fate, (ii) sources and environmental impacts, (iii) toxicity, (iv) sorption of contaminants, and (v) detection and characterization, on microplastics under various environmental conditions [19,20].

This review aims to present the recent studies regarding microplastic applications. The microplastic characteristic and degradation mechanisms in the environment are discussed. In addition, sample, separation, extraction, and detection methods are briefly presented. The recent studies on the source and occurrence of microplastic in various environmental matrices such as seawater, surface water, soil and groundwater, wetland, and air are pointed. Moreover, this review highlights the potential effect of microplastics on humans and soil. Finally, this review summarizes the reported mitigation measures to decrease microplastic loads in the environment.

2. Intrinsic characteristics of microplastics

Microplastics are detected in the environment either as particles directly discharged from industries such as the textile industry (primary microplastics) or as the degradation product and fragmentation of large plastic items (secondary microplastics) [21]. Microplastics differ in terms of composition, type, size, and shape. The most detected microplastics in the environment are polyvinyl chloride (PVC), polyethylene (PE), polypropylene (PP), polyester (PES), polystyrene, polyethylene terephthalate (PET), polyurethane (PUR), and polyamide. The physicochemical properties of microplastic are determined by their composition. Physicochemical properties include density, crystallinity, additives, and surface chemistry [22]. The density of microplastic is highly affected by crystallinity. For instance, PP and PE have the same density as semi-crystalline polymers [23]. Nevertheless, aging time and weathering can change the crystallinity of microplastics. Thus, the physicochemical properties (e.g., size, particle shape, pollutant sorption capacity, and additive leaching) may change also. In addition, their functional group affects the toxicity and mobility of microplastics such as (–COOH, C–O, and C–OH) [24,25]. For instance, the negatively charged sulfonic acid-functionalized PS nano-plastic are detected in high concentration in the plant, while the low concentration of positively charged amino-functionalized PS is detected in plant roots. The surface group of microplastics affects the adsorption of heavy metals and organic pollutants. In addition, the adsorption of ions is highly related to the microplastic's surface roughness which increases as microplastics age in the environment [26–28].

Many shapes and sizes of microplastics are detected in the environment. Pellets, fibers, films, fragments, foam, ellipse, particles, flakes, and lines are reported in the literature. Microplastic sizes broadly differ according to the region [29,30]. This is due to the transformation processes such as biodegradation and weathering, which differ from place to place. The physicochemical properties of Microplastics may change as weathering processes such as oxygen, UV radiation, moisture content, and temperature are taking place [13,31]. Solar radiation, oxidation, and high temperature can

release ketone ester groups in plastics, changing the surface charge from neutral to negative [32,33]. So, microplastics in water and surface soil can transform easily. Furthermore, factors such as length of exposure to the environment, structural chemistry, and environmental conditions influence the physicochemical characteristics of microplastics. For example, eroded microplastic surfaces in aqueous environments are ideal for bacterial colonization and organic and inorganic compound adsorption [22,34].

3. Degradation of microplastics

A lot of mechanisms manage microplastic degradation in the environment. Biological, chemical, and mechanical degradations are the main mechanisms [35]. The degradation of plastic depends mainly on two factors; first, the properties of the polymer, which include structure, chemical composition, and additive. The second is the environmental factors such as humidity, temperature, depositional matrix (e.g., water, sand, soil, terrestrial vs. aquatic), and depositional environment. Combining two or all three degradation mechanisms generally leads to microplastic degradation [36].

3.1. Biological degradation

Many reviews summarized the biological degradation in the different environmental matrices such as seawater, soil, surface water, and wetlands [2,37,38]. The Biological degradation of microplastics mainly involved microbial digestion in breaking the plastic debris into smaller products. The microbial digestion process includes conditional film formation, colonization, bio-fragmentation, assimilation, and mineralization. The plastic fragment must contact ambient water for biofilm formation, developing conditioning film around the plastic fragment. The chemistry of plastic plays a significant role in which types of organisms will attach to fragments. After mechanical and chemical weathering processes, surface pits, cracks, and other holes form suitable environments for subsequent colonization [6,39]. Gao et al. [26] found that environmental factors such as waves and tides could enhance surface roughness in the natural environment, increasing the colonization of bacteria on the fragment's surface. The authors stated that chemistry produced by weathering and surface roughness provides the ideal condition in which bacteria colonize the particles.

When the colonization takes place on the surface of plastic, microorganisms start breaking down the polymers to produce oligomers, monomers, and dimers by releasing exoenzymes. Many studies investigated microorganisms that can degrade many types of plastic [12,40]. For instance, *Aspergillus* sp. can biodegrade LDPE, while *Rhodococcus* can degrade PP and LDPE. *Bacillus subtilis* has been shown to biodegrade polyester polyurethane, and *Zalerion maritime* degrades polyester polyurethane and PE. After degradation, assimilation can take place if the size of plastic after degradation reaches a level that can pass through the cell walls of microorganisms [36,41]. When assimilation starts, the polymer molecules are used as energy and carbon sources. As a result, water, carbon dioxide, and methane are produced

in the final mineralization step [19,42,43]. The characteristics of plastic such as crystallinity, molecular weight, additives, and functional groups significantly affect the plastic breakdown speed. Biodegradation can occur aerobically, producing carbon dioxide and water, or anaerobically, carbon dioxide and methane [44].

3.2. Mechanical degradation

Temperature change and wet/dry cycles may consider mechanical degradation [45]. Mechanical degradation mainly occurs by abrasion, by which the plastic particles rub with natural or other anthropogenic items in terrestrial and aqueous settings. The natural items may include shells, grains, and woody debris, while anthropogenic items may include littered trash, other plastic particles, human-made barriers, and vehicles. The particles produced from mechanical abrasion of microplastic are rounded (particle edges are low sharpness), like the shape of natural sand grains transported over long distances or subjected to repetitive erosion in high-energy environments. Studies using scanning electron microscopy (SEM) have shown that mechanical degradation is also taken place by surface textures that cover conchoidal fractions and grooves. These textures are usually founded on natural sedimentary quarts in littoral zones characterized by grain-to-grain collisions; thus, beaches are the first natural sites for microplastic particles abrasion [45].

3.3. Chemical degradation

The chemical degradation of microplastic occurs at various levels depending on several factors such as polymer properties and the presence of additives and medium and depositional settings. For instance, microplastics on beaches are subjected to more UV radiation than microplastic particles buried in the sediment or swimming at a depth in water [45]. Moreover, the chemical degradation rate of microplastic in seawater is higher than that in freshwater as alkalinity, salinity, and biological colonization differs. Many reviews have discussed the chemical degradation of microplastics in many reviews [12,33,46–49]. Generally, photodegradation of microplastics is started by subjection to UV radiation and oxygen, which produce shorter chain molecules than those of the original. Polymers having C–C bonds such as PE, PS, and PVC do not promote photooxidation.

Thus, without additions, degradation will take place slowly. In contrast, polymers with impurities or structural abnormalities can experience photooxidative as UV light breaks C–H bonds or thermal degradation. The bonds are heated enough to undergo side-group elimination and random scission (normal when heated to rupture point). As a result, free radicals may produce and react with oxygen from those two processes. This reaction leads to cross-linking or chain scission, inert products development, and reduction in molecular weight of the polymer [50]. This reduction in molecular weight resulted in a weaker polymer which easily can be degraded mechanically or biologically [48]. In sites such as ocean floor. In sites such as ocean floors or landfills, thermal oxidation, photooxidation, biodegradation, and abrasion are not enabled; hydrolysis

occurs, especially for aromatic polyesters. This process leads to shorter chains such as ethylene glycol and terephthalic acid [24].

4. Quantitative analysis of microplastics

The quantification process of microplastic that contaminates the environment and ecosystem is challenging and critical as considered an important step for better understanding hazards such as microplastic pollution, which is still an unknown form of pollution [51,52]. Microplastic quantification includes sampling, separation, detection, and characterization [53]. This section discusses the sampling, detection, and analysis of microplastic. In addition, this section gives up-to-date analysis methods for microplastics quantification in the environment.

4.1. Extraction

However, the water sample for microplastic analysis is usually taken from calm waters. The optimum depth is still among the argued issue in the literature. For water sample collection, the first step is to take marine debris using nets/trawls such as Bango trawls or Manta, filter pumps, or epibenthic sledge from the water column [54]. In some cases, pre-processing may be conducted on-site, while the full probe analysis is performed in a laboratory. Recently, a fully automatic Manta has been developed to collect and analyze microplastic [55]. The main advantage of such an automated system is the capability to analyze in situ, which adds time and effort flexibility to the microplastic analysis process. For instance, a smart sampling instrument, “Albatross” has been invented to decrease the collection time to less than 3 min, which means more locations can cover [56]. The scientist designed a new system called “MantaRay” which combines a flow-through pump with an autonomous sensor to collect and evaluate microplastic concentration [57].

Nevertheless, sampling and analysis of microplastics are complex and require strict rules for site and laboratory workplaces. After collecting microplastic samples from the water column cleaning process with ultrapure water and ethanol (70%). After cleaning, the samples undergo sieving, digesting organic matter (without microplastic digestion), density separation, and filtration [43]. The most common method for separating microplastic from water is sieving (filtration). The detected microplastic size determines the filter pore or sieves mesh: the smaller size, the quicker collaging by mineral and organic matter. To remove impurities (organic and inorganic contamination) from filtered samples, further purification is required [58]. Density separation is used for inorganic contaminants such as clay particles and silicate grains. This method does not work with organic matter as plastics have densities like organic matter. Oxidation agents are a feasible and effective solution to remove organic matter. Oxidation agents such as strong alkaline or acidic substances are unsuitable as they negatively affect synthetic polymers [55,59]. Other methods such as microwave digestion and centrifugation may lead to the breaking down, deformation, and decomposition of microplastics. Wet peroxide oxidation (WPO) has been reported as a powerful tool for

digesting organic matter without damaging microplastic. WPO involved the treatment of microplastic samples with 30% hydrogen peroxide and ferrous ion (Fe^{2+}); this process is called Fenton’s reaction. WPO is an effective oxidative method for organic matter removal as it can completely oxidate a wide range of organic matter such as cellulose, grease, and chitin shell. The main advantage of such a process is that plastic can stand the oxidation by peroxide, whereas organic decomposes at nearly 75°C [60]. In addition, WPO can be proper for chitin exoskeleton microorganisms and high-fat content organs. Aside from Fenton’s reaction, other oxidation reagents such as NaOCl , NaOH , KOH , and H_2O_2 alone can be suitable. More strong oxidant agents can remove organic matter effectively, but microplastic can undergo unwanted deformation and degradation [61].

4.2. Identification

The detection of microplastic is complex and challenging as the detection process usually needs a combination of spectroscopy and microscopy analysis. Therefore, the identification of microplastics consists of two actions: first, physical appearance description by optical microscope. Second, identification of chemical composition using spectra either consulting databases or references [21,62].

4.2.1. Microscopy

4.2.1.1. Optical

One of the most common characterization techniques for microplastic analysis is optical microscopy [63]. This method can determine the size and shape of plastic particles and their number. Plastic particles are classified; the first one is visually recognizable from 1 to 5 mm, while the second-one ranges from 1 mm to 20 μm . Hence, the characterization of this group is still a challenge [64]. A high degree of error is the main disadvantage of optical analysis as visual observation does not provide reliable identification of polymers. Therefore, the identification of microplastic’s chemical composition by spectroscopy is an essential step after physical characterization by optical observation [4].

4.2.1.2. Fluorescence

Many microplastic particles can behave as fluorescent dyes; thus, fluorescence microscopy can be used for the physical characterization of microplastic [3]. The plastic surface hydrophobicity degree plays a significant role in finding the range of fluoresces (usually from yellow to dark in terms of microplastics). Normally, green fluorescence (460/525 nm) is preferable to choose for the following reasons: (1) organic matter fluorescence is red. Thus the observation of microplastic under green fluorescence is simple, (2) synthetic plastic fluoresce better in green, (3) green filter membrane has a lower background signal [65]. Nevertheless, the contamination of the microplastic surface due to a change of hydrophobicity can affect the emitted color during the identification process by fluorescence

microscopy. Therefore, including non-overlapping colors' dyes is necessary to differentiate between diverse categories of plastic [66].

4.2.1.3. Scanning electron microscopy (SEM)

Scanning the sample's surface by electron beam can generate high-resolution images [67]. Microplastic has different image morphology than organic and inorganic impurities. Thus, studying SEM images of microplastic is not only used for microplastic characterization but also for studying the erosion process of microplastic by studying the surface textures features [68]. Combined SEM with other analysis tools such as dispersive analysis (EDS) can give detailed details about the composition of microplastic, especially the content of inorganic additives [3].

4.2.2. Vibrational spectroscopy

4.2.2.1. Fourier transform infrared spectroscopy (FTIR)

Vibrational spectroscopy is a non-destructive identification method that measures vibrational energy. The main advantage of FTIR analysis over an optical microscope is that FTIR can differentiate a greater number of microplastic fragments [69]. In addition, FTIR can detect white or transparent fragments (such as PE and PP), which are non-distinguishable due to their white color. Many studies demonstrate that the number of plastic fragments determined by FTIR is eight times higher than that determined by optical microscopy [66].

4.2.2.2. Raman spectroscopy

Identification of microplastic chemical composition can be made by Raman spectroscopy. This method uses a scattering approach applying a laser of defined wavelength for targeting molecules. The elemental composition can be determined by the frequency of scattered radiation [68]. Raman spectroscopy can identify microplastics smaller than 1 μm and provide structural and chemical characteristics, which FTIR cannot do [70]. The combined use of FTIR and Raman techniques is profitable for improving microplastic identification.

4.2.3. Thermo-analytical method

Contrary to microscopy and vibrational spectroscopies, thermo-analytical methods are destructive methods, where microplastic samples thermally destruct under certain conditions [68].

4.2.3.1. Thermogravimetric analysis (TGA)

Calculates the sample mass loss when the temperature rises according to a programmed rate under a controlled atmosphere. TGA techniques provide individualization of polymers and reveal the nature of microplastic as plastics have individual low melting points for each type of polymer [71]. Combining the TGA method with other analytical technologies such as differential scanning calorimetry,

FTIR spectroscopy, mass spectrometry, and gas chromatography resulted in sophisticated tools for investigating materials' thermal properties and composition [72].

4.2.3.2. Pyrolysis–gas chromatography–mass spectrometry (Pyro-GC–MS)

In this method, the products formed by pyrolysis of microplastics are analyzed by gas chromatography coupled with mass spectrometry [73]. Pyro-GC-MS provides a comparable result with FTIR. In addition to Pyro-GC-MS, thermal extraction desorption gas chromatography–mass spectrometry (TED-GC-MS) can give reliable data [72].

4.2.4. Light scattering

4.2.4.1. Dynamic light scattering (DLS)

Dynamic light scattering (DLS) can gain details about small particles' size distribution in solution. Small particles are defined as particles with a size smaller than the wavelength of the irradiating light ($\lambda \sim 800 \text{ nm}$) [74]. DLS can determine particle size using the fluctuations in scattered light intensity because of the Brownian movement of the particles in the solution. DLS analysis can be conducted in situ, giving valuable details about the nanoparticle's formation during photodegradation [75].

4.2.4.2. Nanoparticle tracking analysis (NTA)

Nanoparticle tracking analysis (NTA) can record and visualize nanoparticles in solution by combining laser light scattering microscopy with a charge-coupled device (CCD) camera. NTA and DLS are complemented in particular ways that are beneficial for polydisperse nanosized particles. Lambert and Wagner [62] used NTA technology to trace the formation of nanoparticles produced from PS degradation of PS. Coffee cups made from PS were immersed in ultra-pure water and subjected to UV-Vis light at 30°C. After 14 d, nanoparticles quantity was differentiated; after 56 d, the PS nanoparticles were 3 times that reference vial.

5. Source, occurrence, and fate of microplastics

When plastics are subjected to physical wear, they can gradually break down into smaller microplastic pieces. This section discusses the occurrence and fate of microplastic in different environmental matrices. In addition, it discusses the factor affecting the distribution of microplastics in every matrix.

5.1. Seawater

The main source of microplastics in seawater is the insufficiently treated wastewater which discharged in huge quantities [76]. The spread of microplastic particles in marine environments has been reported by many researchers [77,78] and has been the topic of many recent studies. The marine microplastics exhibit wide ranges of sizes, shapes, and densities; thus, continuous distributions

of these parameters can be used to characterize the whole Microplastics “ensemble” at any one time [34,79]. Moreover, distribution of dynamical properties such as critical shear stress, rising or sinking velocity, and the re-suspension threshold. In addition, the age of microplastics in the marine environment significantly affects their properties [22,80]. Marine microplastics can be classified into seafloor studies and surface water studies. This classification is due to the different plastic types that compose disparate densities [81,82]. Less dense microplastics accumulate on the water surface and shoreline, while more dense plastics accumulate in the seabed or deeper water. Plastic particles with a density lower than seawater density (about 1.02 g/cm³ at 20°C and 1.03 g/cm³ at 0°C) are commonly accumulated, transported, and concentrated by ocean currents, wind, and gyres, resulting in the spread of microplastics within marine environments, and the gathering of less dense microplastics in the five great garbage patches [83,84]. For instance, PP with low density (0.89 g/cm³) cites on the seabed, illustrating these plastic particles involved in a process that increased their density. PE and PP are usually found in ocean water surfaces due to their lower density [76]. Three main processes cause the movement of microplastics in a deep marine environment: (1) thermohaline currents; (2) water column suspended or surface-floating particles; and (3) gravity forced movement in sediment-laden flows. This three-transport mechanism doubled microplastics settling, accumulation, and concentration in deep-sea trenches and submarine canyons [85].

Recently many studies reported the occurrence of microplastics in marine environments. Vazquez et al. [86] reported the occurrence of polychlorinated biphenyls (PCBs) in the Southwestern Atlantic Sea. The results showed that the PCBs' loading rate was between 2.89 and 79.41 ng/L in seawater and 0.07 to 6.61 ng/L dry weight in sediment samples. Similarly, Duan et al. [87] investigated the effect of the plant (Mangrove) on the distribution of microplastics in sediment Nature Reserves in south China. The results showed that the distribution of microplastics was affected by plant species as more PET and fibers were detected on the *Sonneratia caseolaris* while more PS was founded on *Kandelia obovata*. In a recent study, Prarat and Hongsawat [88] studied the distribution of microplastic seawater and beach sand in Rayong province, Thailand. The results pointed out that the average microplastics in seawater and beach sand were 1,781.48 ± 1,598.36 particles/m³ and 33.38.89 ± 264.94 particles/kg dry weight, respectively. Table 1 summarizes the occurrence of microplastics in different environmental mercies worldwide.

5.2. Surface water

The existence of freshwater microplastics across the globe has been pointed out in many studies in the literature [100]. Previous studies reported that microplastic distribution and concentration on the environmental matrix such as water surface, water column, and sediment depend on Wind, streamflow rate, currents, and geographical position. For instance, the microplastic concentration in freshwater

sources near urban areas is high compared to rural settings [101]. Moreover, in freshwater systems such as rivers, microplastics' occurrence, concentrations, and movement are highly dependent on flow rate. For example, Tibbetts et al. [102] found that the concentration of microplastics along the River Tam (Birmingham: England) was changed according to flow velocities, where high concentration was found in spots with low velocity. Similar investigations have reported a high microplastic concentration in dams, lakes, floodplains, and other low-velocity environments [103]. On the other hand, increased flow rate and velocity significantly affect the transport of microplastics. For example, the microplastics flushed in river systems during flood events (flow velocity and quantity increased) [104]. Generally, high flow velocity environments such as rivers and streams act as microplastics vehicles, whereas decreased flow velocity such as lakes behaves as microplastics sink [92]. Thus, the microplastics loading process and other pollutants are the same. On the contrary, rivers, and lakes consider loading sources of secondary microplastics. This can be attributed to the transformation (usual fragmentation) of plastic in those environments due to waves, stream actions, and currents, the same case in the marine environment.

Recent studies reported the occurrence of microplastics in freshwater systems. Gong et al. [89] investigated, for the first time, the occurrence of microplastics in the Liaohe River Reserve, China. The result showed that the fiber microplastics were accounted for 43.48% in sediments and 91.86% in surface water, showing that the source of those microplastics may be domestic wastewater. In addition, the authors reported that 27 and 17 types of polymers were detected in sediment and water, respectively, and polyethylene terephthalate, polystyrene, polyester, and rayon were the main detected polymers. In another study, Ramadan and Sembiring [90] reported the occurrence of microplastics in the biggest freshwater reservoir in Indonesia. The author attributed that to this reservoir's water source, which streamed from the polluted river of Citarum. In addition, they found that the majority of microplastics were fragmented polyethylene. Blankson et al. [91] studied the occurrence of microplastics in the Densu River, Ghana. The results showed that the pollution by microplastics spread over the Densu River to cover all the studied compartments. In another study, Pisku and Astel [92] studied the occurrence of microplastic in two river flow in northern Poland. The results showed that microplastics polluted 62.5% of collected water samples.

Moreover, the season variations affect the concentration of microplastics as the number of plastic particles was in the following order: autumn (52 particles) < summer (64 particles) < spring (75 particles). The FTIR analysis denoted that the identified polymer types were polystyrene, polyester, polypropylene, polyvinyl chloride, and polyethylene. Similarly, Fan et al. [93] studied the spatiotemporal dynamics of microplastics in an urban river network in eastern China. The results pointed out that spatial factors did not significantly affect the concentration of micropollutant concentrations, while temporal factors dramatically affect the occurrence of microplastics as the

Table 1
Microplastic type, concentration, and location in environment matrices around the world

Type of plastic	Acronym	Sample type	Location/Region	Concentration	References
Polychlorinated biphenyls	PCBs	Seawater	Southwestern Atlantic	2.89 to 79.41 ng/L	[86]
Polyethylene terephthalate, polypropylene, polystyrene and polyamide	PET, PP, PS, and PA	Mangrove	South China	(2,835 ± 713 items/kg d.w.)	[87]
Polyethylene	PET	Beach sand and seawater	Rayong province, Thailand	338.89 ± 264.94 particles/kg d.w (beach sand); 1,781.48 ± 1,598.36 particles/m ³ (seawater)	[88]
More than 27 polymers were identified	–	Reserve	Liaohu River Reserve, Northern China	62.29 ± 54.30 items/kg (sediment); 0.11 ± 0.04 10 ⁻² items/L (surface water)	[89]
Polyethylene	PET	Freshwater reservoir	Jatiluhur, Indonesia	0.71 × 10 ⁴ – 4.59 × 10 ⁵ particles/km ²	[90]
–	–	Water, sediment	Densu River, Ghana	4.0 ± 0.82 per 10 g (sediment) 1.5 ± 0.84 per 10 mL (water)	[91]
Polyethylene, polyvinyl chloride, polypropylene, polyester, and polystyrene	PET, PVC, PP, PES, and PS	River	Northern Poland.	3.6–4.2 items per (100 mL) sample	[92]
Polytetrafluoroethylene, and polypropylene as	PTFE, PP	River network	Eastern China	2.3 ± 1.2 to 104.6 ± 5.6 particles/L	[93]
Polyester and polypropylene	PES and PP	Soil	Canary Islands, Spain	159 ± 338 and 46 ± 92 items/kg	[94]
–	–	Soil	Central China	2,522 ± 1,276 items/kg	[42]
Polypropylene and polystyrene	PP and PS	Groundwater	South India	2–80 items/L	[95]
Polyethylene, polypropylene, polystyrene and polyvinyl chloride	PE, PP, PS, and PVC	Groundwater	Victoria, Australia	38 ± 8 microplastics/L	[96]
Phthalate esters	PAEs	Wetlands	China	0.31–1.52 µg/L (water); 450–2096 µg/kg dry (sediment) 210–937 µg/kg d.w. (mangrove plants)	[94]
Polyester, polystyrene, polybutadiene, and polyethylene	PES, PS, PBD and PE	Atmosphere	Jakarta-Indonesia	Average: 15 particles/m ² /d	[98]
Polyester, polyamide, and nylon	PES, PA	Indoor air	Kuwait	3.2 and 27.1 particles/m ³	[99]

concentration in the wet season was largely higher than in dry seasons.

5.3. Soil

Many studies reviewed the occurrence of microplastics in soil [105–107]. Sewage sludge landfill, plastic film mulching, application of compost, flooding of wastewater, irrigation, atmospheric deposition, and car tires debris were reported as the main sources of microplastics in the soil matrix [108]. The main sources of microplastics in the terrestrial soil are industrial production, agricultural production, and urban activities. In the case of using sludge

as fertilizer for agriculture, it made a route for microplastics to enter agriculturally [109]. Because of the large spread of agricultural land, organic fertilizer and plastic film used in agriculture are considered the main source of microplastic in soil. As PVC and PE are intensively used in agricultural production, they are the main polymers usually found in agricultural film. PVC films have good heat preservation and poor light transmission, while PE has good light transmission. The agricultural film has a low recovery rate which leads to its presence in the long term in farmland soil [17,110]. Microplastic from atmospheric deposition is also considered an important source in soil. The amount of microplastic in the atmospheric

environment, which is deposited every day, is between 29 and 280 pieces/m².

Moreover, around 10 tons of fibrous microplastics are deposited in the atmosphere every year [111,112]. Microplastics in soil usually move vertically (animal carrying, soil erosion) and horizontally (surface runoff, wind). The microplastics move from surface to deep soil (Surface runoff, Wind). The microplastics move from surface to deep soil [113]. Leaching, preferential, and soil fissures are also mechanisms for microplastic migration from surface to deep soil [114]. It is important to mention that soil is not the final sediment of microplastics but is also considered a microplastic source for the water environment. A study by Rezaei et al. [115] revealed that 60% of microplastics in soil migrate to river basins.

Recent studies reported the occurrence of microplastics in soil environments. Pérez-Reverón et al. [94] reported the presence of microplastic in two types of soils (clay-loamy and sandy-loam) which are irrigated by water from desalinated brackish water and recycled wastewater in the Canary Islands, Spain). In another study, Liu et al. [42] studied the occurrence of microplastics in four different layers (paddy field, dry land, plastic greenhouses, and grassland) in the Sheshui River, China. The results showed that the lowest microplastics were found in greenhouses, while dry land had the highest value of microplastics. Plastic fragments and fiber were the most found plastic shapes, and size was less. The authors found that the microplastic sources may be attributed to applying organic fertilizer, wastewater irrigation, and plastic mulching film.

5.4. Groundwater

The main process that drives pollutants to reach groundwater is leaching. Microplastic transport through bio pores is a possible mechanism for groundwater contamination. Soil microplastics can reach groundwater by water infiltration and surface runoff. Soil microplastics can reach groundwater by water infiltration and surface runoff [116]. Another source of microplastics may be attributed to landfill leachate. When the groundwater contaminates by landfills, a contaminated plume will arise, and the connected aquatic environment will also be contaminated. In addition, the wet (intense) and dry (long) cycles speed up the dispersion leachate around areas, creating microplastic contamination of subsurface water. Recently, many studies reported the presence of microplastics in groundwater. Kim and Lee. [117] expressed that microplastic contamination in groundwater is not clear until now; thus, many efforts to establish microplastic detection systems for groundwater. In this regard, Ryu et al. [118] constructed a mode by finite element method to simulate the transport of microplastics in groundwater. The results showed that fast water flow velocity, low diffusivity, and high soil porosity might decrease the number of microplastics discharged into groundwater. In another study, Bharath et al. [95] studied the occurrence of microplastics in groundwater around two municipal solid waste dumpsites in South India. The results showed that all groundwater samples were polluted with microplastics. The concentration of microplastic was in the range of 2–80 items/L. White-colored microplastics were dominant

with 38%, while yellow particles were subservient with 2%. In addition, 70% of microplastic was nylon type while polythene was 1%. In a recent study, Samandra et al. [96], for the first time, reported the occurrence of microplastics in ground-water. The found microplastics were polyethylene, polystyrene, polypropylene, polyvinyl chloride, polyethylene terephthalate, polycarbonate, polymethylmethacrylate, and polyamide. These polymers are commonly detected in the environment. The size of detected microplastics was 18 to 491 μm , while the number of microplastic detected was 16 to 97 particles/L. PE and PVC were 59% of detected particles.

5.5. Wetland

Microplastics sources in wetlands are from nearby human activities [119]. Sewage discharge is considered the main human activity that produces microplastics [34]. The continuous discharge of wastewater into the environment leads to microplastic accumulation in the sediment resulting in the contamination of wetland by microplastics. Another source of microplastics in wetlands is waste from aquaculture [120]. For instance, the decomposition of plastic woven bags, polystyrene foam buoys, and fishing nets was found in mangrove wetland. Precipitation-induced surface runoff tidal or wave-induced plastic decomposition are processes that introduce microplastics into wetland ecosystems. As wetlands have fluctuating water tables, abundant creatures, and silted sediment, the vibrant biogeochemical cycling led to uncertainty of wetland microplastic distribution [121]. The most detected microplastics in wetlands is polystyrene, as these polymers are used in daily needs such as cups, water pipes, and appliance housings [122]. The hydrodynamic conditions significantly affect the distribution of microplastics in wetlands. Turbulence caused by rainfall affects the distribution of microplastics in wetlands as atmospheric microplastics may enter wetlands with rain. Moreover, the concentration of microplastics is high in summer and low in winter due to precipitation [123].

Recent studies reported the occurrence of microplastics in wetlands. Xia et al. [124] studied the migration characteristics of microplastics from sinks (sediment, effluent, agriculture waste, and surface water) to Huixian Wetland, Guilin. The results showed that agricultural wastes and wastewater effluent were the major sources of microplastics in wetlands. In addition, for the first time, the authors reported the occurrence and removal of small size microplastics (50–500 μm) in wetlands. In another study, Wang et al. [97] studied the occurrence and distribution of phthalate esters in mangrove wetlands (Dongzhai Harbor, China). The results showed that the concentration of phthalate esters in mangrove plants was 210–937 $\mu\text{g}/\text{kg}$ DW. Reynolds and Ryan [125] studied the ingested microplastics by water birds living in contaminated wetlands in South Africa. They analyzed 283 fecal samples and 408 feather brushing. The results showed that microplastics contaminated 10% of feather samples and 5% of fecal samples.

5.6. Atmosphere

The primary source of atmospheric microplastics is the erosion of synthetic rubber tires, synthetic textiles, and dust. In addition, atmospheric microplastic is causing 7%

of ocean-contaminated microplastics [126]. Other sources of microplastics in the air may be plastic fragments from house furniture and clothes, waste incineration, materials in buildings, particle resuspension, industrial emissions, particles released from traffic, sewage sludge used as fertilizer, synthetic particles used in horticultural soils [127–130]. In addition, synthetic textile is one of the main sources of airborne microplastics in both outdoor environments and indoors [131]. The distribution and fate of airborne microplastics are controlled by many factors such as wind speed, vertical pollution concentration gradient, particles precipitation, and temperature [132–135]. Moreover, urban topography, thermal circulation, and local meteorology may cause wind modulation, affecting the distribution of outdoor air contaminations [136,137]. Microplastic residence time in the atmosphere is dependent on Wind, rainfall, particle size, and local condition, resulting in sedimentation. Lighter microplastic particles such as polymers can be moved by Wind [138,139].

Recent studies have been reported the occurrence and distribution of atmospheric microplastic. Purwiyanto et al. [98] investigated the deposition rate and the properties of atmospheric microplastics in Jakarta. The results showed that polymers such as polystyrene, polyester, polyethylene, and polybutadiene were detected. In addition, the deposition rate ranged from 3 to 40 particles m^2/d . Moreover, fewer microplastic particles are deposited in the dry season than in the rainy season. In another study, Chen et al. [140] collected samples from nail salons to study microplastics' physical characteristics, concentration, and polymers. The results referred that nail salons suffer from severe microplastic pollution. In addition, air conditioners caused a higher concentration of microplastics in nail salons. In another study, Liu and Schauer [141] investigated the link between SARS-Co V-2 transmission and airborne microplastics. The result showed that the limiting spread of SARS-Co V-2 was related to airborne microplastic management. In a recent study, Uddin et al. [99] examined the occurrence of microplastic in indoor environments in Kuwait. The results showed that the concentration of microplastics in indoor air ranged between 3.2 and 27.1 particles $be\ m^3$. In addition, the study examined the effect of location and type of air conditioning on indoor microplastics while no effect was observed about the absence/ presence of carpets. In another study, Pandey [142] investigated the occurrence of microplastics in street dust in Varanasi city, India. The results showed that all street dust and suspended dust samples were contaminated by different colors and shapes of microplastics. The detected microplastics were less than 1 mm, where most detected polymers were polystyrene, polypropylene, polyethylene terephthalate, polyethylene, polyvinyl chloride, and polyester. Moreover, the analysis of samples revealed that heavy metals such as cadmium and magnesium were presented on microplastics.

6. Effects and potential risks of microplastics

6.1. Human

As microplastics can mix into groundwater, the possibility of reaching the human body is high. Reaching the

human body through the food chain (soil-earth-worm-chicken) has been reported by many studies [143]. The accumulation of microplastics in chickens has adverse effects on human health. In addition, PS polymer can transfer through roots of plants and reach leach and stems; thus, PS may find its way to enter humans easily [144]. Until now, no evidence of the effect of microplastics on humans. However, the accumulated microplastics in soil may transfer to the human body through the food chain [145].

6.2. Soil

As mentioned-above, many studies reported the occurrence of microplastics in different polymers, shapes, concentrations, and sizes. Nevertheless, little information about the effects of microplastics on soil and plants is known [109,146]. A new study by Maršálek and Svobodová [147] reported the short-term effect of microplastics on roots empirically. While microplastics positively increased the shoot and root biomass, they negatively affected soil properties such as aggregation and microbial activity. The authors also reported that microplastic's effect on plants depends on many factors such as concentration level, polymer type, shape, plant species, and soil type. Microplastics can affect the soil's dissolved organic matter content.

Liu et al. [148] found that 7% W/W of PP microplastics did not affect soil organic matter contents, while 28% W/W concentration of PP microplastics dramatically increased the nutrient content. In another study, Machado et al. [149] investigated the effect of microplastics on soil structure. The results showed that microplastics affected water-stable aggregates, water holding capacity, and soil bulk density. In another study, Zhang et al. [74] reported that the linear shape of polyester might enhance the entanglement of soil particles to form clod. Thus, the polyester microfibers may increase soil macropores. Another study by Rillig et al. [150] reported that microplastics might act as carbon storage in soil due to plastics' high carbon content (90%). In a recent study, Dong et al. [112] investigated the effect of the interaction of arsenic with microplastics on soil properties. The results showed that microplastic reduced the bioavailability of arsenic in soil, which inhibits the effect of arsenic on soil's chemical and microbial properties.

7. Microplastic management and mitigation

The stable and non-degradable microplastics may negatively affect humans and the environment [1]. Therefore, mitigation measures are important to reduce plastic loads in the environment. One of the important steps to reduce microplastic pollution loads in the soil is to avoid or reduce using plastic in food production systems [151]. Reasonable usage and/or recycling of plastic mulch films may reduce microplastic pollution in the agriculture system [152–156]. Regulations are necessary to control low-quality plastic film, which causes a high pollution load from entering the market.

Moreover, the use of multi-year agricultural plastic films should be promoted. In addition, bioplastic is a promising solution as it can be completely or partially degraded in the environment by microorganisms [157]. This type of

plastic is an important step toward a sustainable practice in agriculture and the plastic industry [158].

Recent studies reported microplastic removal techniques besides mitigation measures to reduce microplastic load [47,159–161]. Hu et al. [162] investigated the degradation of microplastic using a hydrothermal coupled Fenton system. The results showed that 95.9% of polyethylene is removed from the system after 16 h while after 12 h the weight loss was 75.6%. In another study, Wang et al. [163] developed new biodegradable sponge materials for microplastic removal from the water system. The sponge was fabricated from plant-based protein. The microplastic removal experiment showed that the new sponge could remove 81.2% of microplastics at a pH range of 6–9. The results indicated that the sponge-based removal method proposes a solution for microplastic removal from the water environment. Wang et al. [163] studied the performance of constructed wetland for tertiary wastewater treatment to reduce microplastic load. The results showed that more than 88% of microplastics were removed using constructed wetland, leading to a dramatic decrease in microplastic load, thus hindering them from entering the aquatic systems. The study provides a promising solution for microplastic removal by constructed wetlands.

8. Recommendations and future prospective

Last two decades, microplastics have gained more attention from the scientific community. Nevertheless, the previous research emphasizes the occurrence and fate of microplastics and their distribution in soil, air, sediments, lakes, rivers, and oceans. Moreover, many investigations examined the remediation technologies and ecotoxicity of microplastics. To deal with global challenges such as microplastics, several research gaps, priorities, and challenges are described:

- Future research should focus on standardizing the microplastics extraction and identification. Developing a multi-analytical approach is crucial for gaining accurate details on the distribution, environmental impact of microplastics, and their degradation path, which may form nano-plastic.
- In addition, the need for reliable, exhaustive, and cost-effective analytical methods for microplastic identification is essential.
- More studies should focus on the effect of concentration levels, polymer type, and shape on soil properties and plant performance in a wide range of soils type and plant species.
- More examination should focus on the effect of the combination of microplastics and adsorbed matters such as micropollutants and heavy metals.
- More research should address improvement and production of bioplastics to replace plastic.
- The scientific community does not yet study the effect of microplastics on human health. Evaluating and enhancing the removal methods for microplastic treatment from contaminated water, soil, and air is an urgent need to hinder human health hazards.
- Developing and addressing the regulation and

legislation that would regulate the spread of microplastic at international and national levels is needed.

9. Conclusion

Microplastics have emerged as a new type of pollutant in aquatic environments. On a global scale, the presence of microplastics in seawater, soil, rivers, lakes, and air has increased, attracting the attention of scientists, politicians, and the public. However, there is currently a lack of knowledge concerning desperation, rapid monitoring, and affecting factors of microplastics. The joint toxicity of microplastics and other contaminants is not fully covered, especially in real ecosystems. Although there is no direct proof that exposure to microplastic causes harm to human health, the toxicity of microplastics or adsorbents/additives to human cells and biota should be given more consideration. In future studies, it is critical to look at the residual, excretion, and bioavailability of microplastics or adsorbents/additives in biota and people. Future research should learn from systematic research methodologies, characterize the diverse ecotoxicological consequences of microplastics, and summarize the deep connection between toxicological mechanisms and eco toxicological appearance. This will aid in the establishment of a comprehensive framework and guiding principles for biosphere protection in the future.

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