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Review article

Occurrence, detection and ecotoxicity of microplastics in selected environments-a systematic appraisal

Elizabeth Oyinkansola Omotola [a,b], Ganden Supriyanto [b,*]

[a] *Department of Chemical Sciences, Tai Solarin University of Education, Ijebu Ode, PMB 2118, Nigeria*
[b] *Department of Chemistry, Airlangga University Surabaya Indonesia, Indonesia*

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ABSTRACT

Microplastics (MPs) are being released into the environment in large quantities, especially in less developed parts of the world. This group of pollutants is mostly leached into the environment through heavy plastic dumpsites, pharmaceutical and personal care product containers, hospital wastes, plastic package accessories, and litter from food packaging. Consequently, these compounds are found in different compartments of the ecosystem, such as soils, sediments, biota, and, surprisingly, drinking water. The present study systematically appraised recent studies on MP pollution in the Asian and African environments. It also summarized the trends in the methods for the environmental monitoring of MPs and the removal strategies that have been employed. From the data gathered, the two key instrumentations involved are the microscopes for visualization and the Fourier transform-infra-red (FT-IR) spectrometer to classify or characterize the MPs. Based on the surveyed works of literature, China and South Africa have relatively more information on MP contamination of diverse matrices within their countries. Meanwhile, studies on the status of MP contamination should be conducted across all countries. Hence, this study becomes an eye-opener regarding the commencement of research works on the MP contamination of the environment, especially in other Asian and African countries with little or no information. Furthermore, the literature on ecotoxicity studies of MPs was investigated to ascertain the toxic nature of these compounds. This aspect of research is vital because it serves as a prerequisite for the remediation of these compounds. Microplastics have been declared lethal to biotic components, so all hands must be on deck to continuously remove them from the environment.

1. Microplastics: an overview

Plastics are a source of improvement, jobs, and innovation worldwide. However, their presence in the environment has remained worrisome. This is due to the fact that they have been found in bits or in whole as microplastics (MPs) in the different environmental compartments of the world. Microplastics are among the relatively new sets of micropollutants and have been defined as organic polymers (synthetic) with a size of <5 mm [1–3]. Nevertheless, most of the definitions given in published articles did not include a lower size limit. In a published article by Duis and Coors, the size of MPs, as stated, was between 1.0×10^{-4} mm to 5 mm [2]. The first study that reported the presence of MPs in the environment was conducted in California in 2011 b y Moore et al. [4]. Moore and colleagues reported the levels of MPs in river surface waters in the San Gabriel River, Los Angeles River, and tributary Coyote Creek.

* Corresponding author.
E-mail addresses: omotolaeo@tasued.edu.ng (E.O. Omotola), ganden-s@fst.unair.ac.id (G. Supriyanto).

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Fig. 1. Microplastic pollution of the environment.

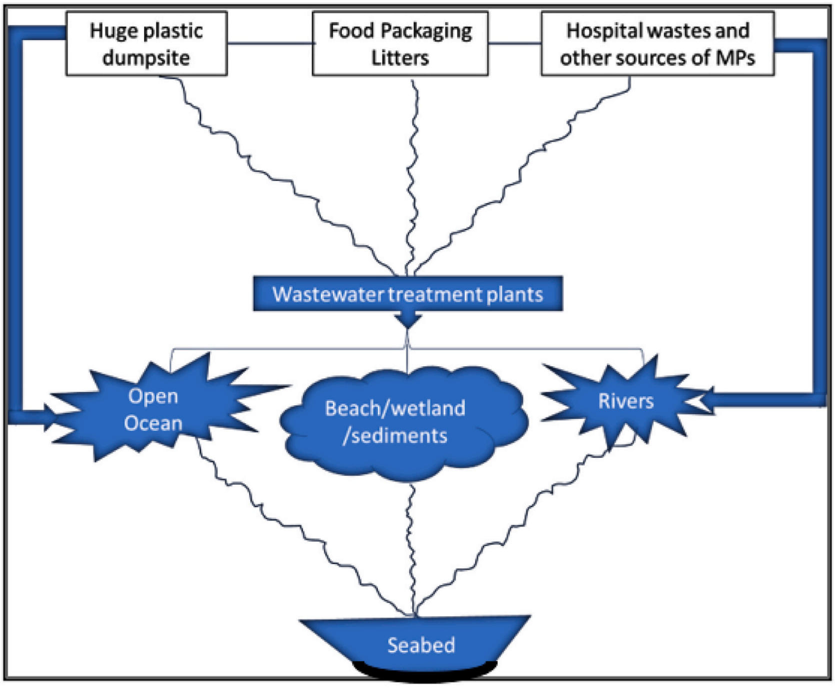

Fig. 2. Transport of microplastics.

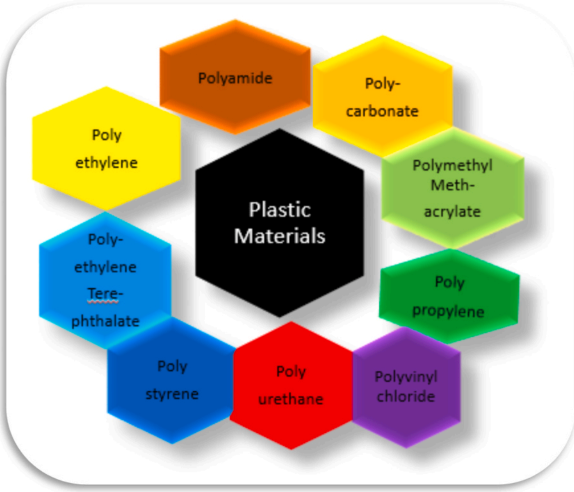

Fig. 3. Chemical composition of microplastics.

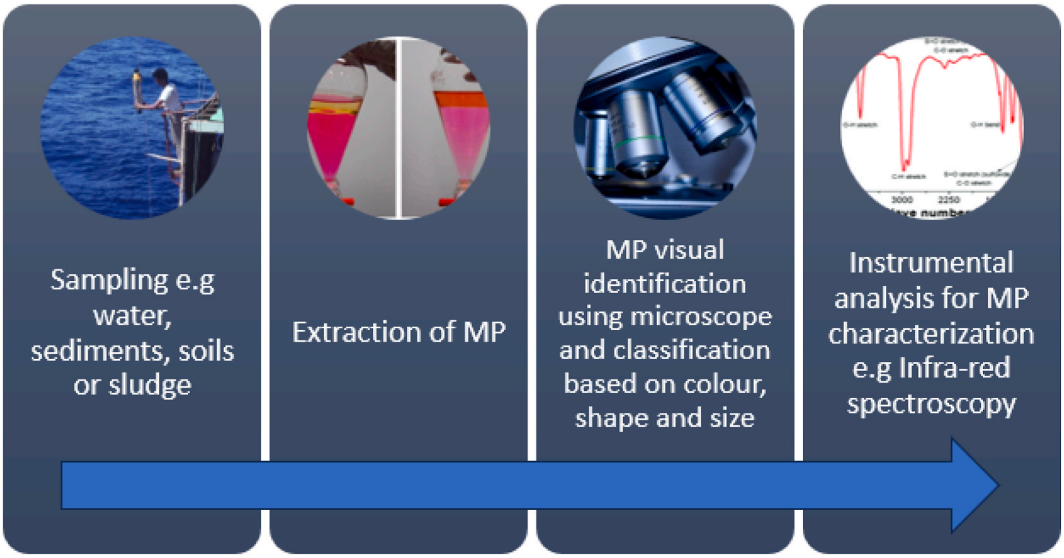

Fig. 4. Procedure involved in the analysis of MP in water samples.

The report confirmed substantial temporal variations in plastic contamination levels resulting from diverse wet and dry weather events, such as run-offs [4]. Run-offs play a chief role in transporting plastics into freshwater systems, leading to several tons of MPs in the water ecosystem. For instance, according to research on MP fibers, 5000 g of polyethylene fabric can release up to 6 million fibers during a laundry cycle [5,6], and a 6000 g wash load can release 700 000 fibers during each laundry cycle [6,7]. All these pollutants end up eventually in the environment through run-offs. Meanwhile, MPs are being released into the environment in large quantities, especially in less developed parts of the world. These groups of pollutants are mostly leached into the aquatic ecosystem through heavy plastic dumpsites, pharmaceutical and personal care product containers, hospital wastes, plastic package accessories, and litter from food packaging, as shown in Fig. 1. Furthermore, MPs have been reported to be recalcitrant and have long-range transport [8]. They are ubiquitous in the marine environment. Remarkably, beaches have been documented to have extremely high levels of MPs [2]. Aside from the marine environment, sediments have also been ascertained to be sinks for MPs [9].

Moreover, offshore areas are predominantly important in identifying MP pollution as they have been reported to be sources of ocean MPs and sinks of land imports [10]. Also, Rivers have been identified as an important pathway through which land MPs are imported into marine [10], with an estimate of over two million tons of plastics transported by them annually [11]. Surprisingly, MPs are now detected in drinking water, following a comprehensive published article on the presence of MPs in tap water and bottled water [12]. The COVID-19 pandemic has also been associated with the increase of MPs in the ecosystem because significant plastic waste was generated during the period [13]. They consist of personal protective equipment such as face masks, disposable gloves, plastic syringes and needles, and other medical supplies. The transport of MPs is shown in Fig. 2. It is worth noting that MPs are hazardous to the environment [8] and require urgent attention regarding their removal from the aquatic ecosystem.

Microplastics can be classified based on their chemical compositions; however, information is still scarce and scanty regarding their categorization according to their size, shape, and electrical charge [8]. These features will undoubtedly provide more insights into the understanding of the fate of MPs. The chemical composition of MPs is presented in Fig. 3, and they are based on the majority of the standard plastic (with polymer composition) produced all over the world [14]. The pollution of the environment by MPs can undoubtedly be linked to the world's production of plastics, which has increased exponentially over the ages [15]. However, it has been observed in Europe that plastic production has been constant in the last decade compared to other continents [15]. Consequently, microplastic pollution is almost inevitable since plastic production is massive worldwide. Although plastic pollution, especially in the marine environment, has been an issue for some time (Carpenter and Smith, 1972), it remains a worldwide challenge.

Consequent to the problem of MPs in the environment, researchers are continually making frantic efforts to understand the occurrence and fate of these pollutants. Therefore, this research aims to appraise the occurrence pattern of MPs, especially in Africa and Asia, where there are few or no policies guiding the monitoring of plastic waste. It also focuses on the various methods of detection of MPs and their ecotoxicity studies. This review article will go a long way, serving as an eye-opener to African countries for the need to monitor the level of MPs as there is scarce and scanty information on these pollutants in the African environment.

2. Trends in the analysis of microplastics

The analysis of different matrices for the detection of MPs commences with sample collection (Fig. 4). The samples are treated for the extraction of MP based on the organic content of the matrix. For instance, the organic content of wastewater samples is higher than that of surface water samples; hence, the extraction of MPs using the wet digestion method is carried out to completely desorb the MPs from the organic matter [16,17]. One of the reagents used for wet digestion of the water sample is hydrogen peroxide (30 %) [18]. Other methods for extracting MP are documented by Huang et al. [19]. Filtration, using appropriate sieves depending on the sizes of MPs of interest, is usually carried out directly on clear water samples. This step is thereafter followed by the visual identification and counting/measurement of specific MPs using appropriate microscopes [18]. The final step involved in the MP detection is an instrumental analysis for MP identification using appropriate spectroscopic techniques (Fig. 4). Generally, the method described in Fig. 4 is applicable to the effective detection of MPs in different environmental matrices.

The instrumental techniques that have been used in the detection and quantification of MPs include Infra-red spectroscopy, gas chromatography/mass spectrometry (GC/MS), nuclear magnetic resonance, and size exclusion chromatography [20,21]. These techniques confirm the specific polymer detected, which could be, but not limited to, polyethylene, polyethylene terephthalate, polyvinyl chloride, or polystyrene. More than a few reviews on MP detection methods have been published recently [21–24]. These reviews corroborate the information provided in the present article. Previously, the method of analysis was centered on light microscopy [21], but the technique could not provide the chemical composition of specific MP, such as the polymer type. One of the widely employed spectroscopic techniques for polymer identification is the Fourier transform infrared microspectroscopy (μ-FTIR) [10,19,25]. This technique is capable of producing spectra that can be matched to library standards [21]. The development of the μ-FTIR technique enhances the substantial characterization of MP and allows particle chemical mapping [21]. In fact, there is a possibility that sample filtrates can be scanned automatically for fibers, microparticles, and tentative polymer when a detector, such as a focal plane array detector, is coupled to a μ-FTIR spectrometer [26]. Compared to the conventional FTIR, which is limited to MPs over 10 μm due to diffraction limit considerations, Raman microspectroscopy can provide detection of MPs of about 1 μm [27]. Sometimes, the identification of polymers may be complicated; this occurs when the polymers are weathered, thereby producing spectra varying from the neat standards of such compounds [21]. Consequently, some researchers overcame this challenge by creating libraries of such weathered polymers [28]. Atomic force microscopy and attenuated total reflectance (ATR-FTIR) have also been employed to achieve similar but may not be able to give optimum results for samples containing numerous minute target compounds [21].

3. Recent occurrence pattern of microplastics in Asia

Due to the rapid economic and demographic growth, alongside rapid urbanization, Asia has been considered a hot spot for plastic pollution [29]. A recent review article documented the MP loads in mangrove water and Asian sediments [30]. These pollutants are abundant in South Asia, from Mount Everest to the Indian Ocean [31]. In this part of Asia, unregulated plastic waste generates over 35 million tons of MPs per annum. Among the countries that contribute a higher percentage of plastics to the Indian Ocean are Bangladesh, India, and Pakistan, which contribute 94 % of plastics [31]. Mehmood and colleagues reported that South Asian countries account for approximately 25 % of the global population, with 91 % of residents in India, Bangladesh, and Pakistan. It is worth noting that the data presented in this study were not altered or changed to uniform units to avoid errors with respect to the presentation of the authors' results since different matrices for MP pollution were considered.

In China, specifically in the Jiangsu coastal area, the distribution of MPs was investigated in wastewater treatment plants (WWTPs), rivers, and offshore sea [10]. Xu and team members reported the highest average abundance of MPs ranging from 13.7 to 19.7 item/m^3 in WWTPs. A significantly higher number of MPs in WWTPs, ranging between 91 and 175 MP/L, was earlier reported by Kwon et al. [18]. This value cannot be compared to the low average abundance of MPs found in the river and offshore sea within the Jiangsu area of China, ranging from 3.7 to 5.9 item/m^3 and 3.1 to 3.5 item/m^3, respectively [10]. The relatively low levels of MPs found in the River in Jiangsu show that the processes involved in the wastewater treatment have some degree of ability to remove MPs before the final release of the effluents into the environment. Microplastics persist and accumulate in the environment [32]; for this reason, their

Table 1
Occurrence pattern of microplastics in the Asian and African environments.

Continent	Country	Types of MP detected	MP Size	Abundance	Sample Matrix	Instrumental Analysis	Additional Information	References
Asia	China	PA, PE, PVC, PP, PS, and RA	1–5 mm	3.1–3.5 items/m^3	Offshore sea, rivers and WWTPs	FTIR microspectroscopy	MPs were widely present (3.1–3.5 items/m^3) in the offshore area.	(Xu et al., 2023)
	India	PET, PVC, PP, PE etc.	<1 mm (90 %)	1411 pieces/kg	Soil	FT-IR and GC-MS	PE was also dominant in Indian dumping site soils, accounting for 55 % of total MP.	(Tun et al., 2022)
	China	PP, PE, nylon, PS, PC, and PET	No large plastic items (>10 mm) were found in the study	19.1 ± 7.2 items/individual	Intestinal tracts of East Asian finless porpoises (*Neophocaena asiaeorientalis sunameri*)	Raman spectroscopy	Fibers, blue items, and PP were predominant in shapes, colors, and plastic materials, respectively.	(Xiong et al., 2018)
	Malaysia	Natural polymer, PAA, HDPE, and PEST	≤0.005–0.050 mm	114 to 689 MP/m^2/day	Atmosphere (atmospheric deposition)	Micro-Fourier transform-infrared spectroscopy (μ-FTIR)	Natural polymer (cellulose) was the dominant type (51 %), with PAA having the highest proportion of synthetic MP (40 %), then HDPE (16 %), and PEST (13 %).	(Hee et al., 2023)
	South Korea	PE, PP, PS, PEST, PU etc.	0.02–5 mm	15–9400 particles/m^3	Deep sea waters	μ-FTIR	The aggregated fraction accounted for 0–28.6 % (average, 3.4 %) of total MPs.	(Eo et al., 2021)
	Japan	PE, PET, PS, PVC, and PP	0.195 and 4.780 mm	1.92 ± 0.12 MP/individual	Dried fish (*Etrumeus micropus*)	Micro-Raman spectroscopy	PE (35 %), PET (26 %), PS (18 %), PVC (12 %), and PP (9 %).	(Piyawardhana et al., 2022)
	China	ER, PET, PR, and PA	0.05–0.20 mm.	6.0 ± 15.4 items/kg	Surface sediment	μ-FTIR.	ER (28 %), PET (25 %), PR (25 %), and PA (9 %) were the main MP polymer components present.	(Wang et al., 2021)
	Republic of Uzbekistan	PU, SR, CPE	0.02–0.05 mm	182 to 17 841 items/kg	Dryland desert soils	laser infrared imaging spectrometer	PU (37.3 %), SR, (17.0 %), and CPE (9.8 %) accounting for 64.1 % of all MP polymer types present in the sample matrix.	(Zhang et al., 2023b)
	Philippines	PU, PE, PMMA, PET, PP etc.	<1 mm (90 %)	24 000 pieces/kg	Soil	FT-IR and gas chromatograph mass spectrometer (GC-MS) for the analysis of plastic additives	PE was the polymer type with highest abundance, mounting to 26 %	(Tun et al., 2022)
	Republic of Korea	–	–	–	WWTPs	–	91-175 MP/L	(Kwon et al., 2022)
	Vietnam	PET, PP, PE etc.	<1 mm (90 %)	11 337 pieces/kg	Soil	FT-IR and GC-MS	PET was a major polymer of MP in soils from Vietnam dumping sites	(Tun et al., 2022)
	The East Asia Seas [East China, Korea Strait, Japan Sea, Okhotsk Sea, Bering Sea, Chukchi Sea, Beaufort Sea, Nordic Sea and Arctic Central Basin]	PEST, RA, and PTFE	0.30–2.00 mm	2.91 ± 1.93 items/m^3	Surface water (Seas and oceans)	μ-FTIR.	The dominant microplastics in the near-surface water samples were polyester fibers.	(Huang et al., 2022)
	China	–	0.5 to > 5.0 mm	Density: 4137.3 ± 2461.5 n/m^3	Surface water (Estuary)	Visual identification via stereomicroscope	Plastic particles (>5 mm) were recorded with a maximum size of 12.46	(Zhao et al., 2014)

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Table 1 (*continued*)

Continent	Country	Types of MP detected	MP Size	Abundance	Sample Matrix	Instrumental Analysis	Additional Information	References
							mm, while MPs (0.5–5 mm) constituted more than 90 % by number of items.	
	Indonesia	PET, PP, PE etc.	<1 mm (90 %)	6061 pieces/kg	Soil	FT-IR and GC-MS	In Indonesia, PE was major polymer, accounting for 37 % of total MP	(Tun et al., 2022)
	China	–	0.5 to > 5 mm	Density: 0.167 ± 0.138 n/m^3	Sea water	Stereomicroscopy	–	(Zhao et al., 2014)
	China (South China)	Mainly fibers, PP and PE		45 200 items/m^3	Coral reef surface waters	–	Pollution load index ranged from 6.1 to 10.2 in the sampled coral reef ecosystems.	(Zheng et al., 2023)
	Laos	PS, PP, PE etc.	<1 mm (90 %)	4651 pieces/kg	Soil	FT-IR and GC-MS	PE was the polymer type with highest abundance, accounting for 49 %.	(Tun et al., 2022)
	China	PP, PE, PET, and PVC		0.48 ± 0.28 items/L	River water	The polymer type of the MPs detected was identified using a Renishaw inVia Raman microscope with an incident laser of 785 nm	Polypropylene was the most frequently identified MP.	(Liu et al., 2023)
	Cambodia	PET, PP, PE etc.	<1 mm (90 %)	4360 pieces/kg	Soil	FT-IR and GC-MS	In Cambodia, PE occupied 50 % of the total MP, followed by PP (26 %), PET (18 %) and PS (2 %).	(Tun et al., 2022)
Africa	South Africa	PE	–	0.14 ± 0.19 to 0.21 ± 0.25 items/g	Mussel species; *Perna* and *Mytilus galloprovincialis*	Fourier-transform infrared spectroscopy (FTIR)	Microbeads were the predominant MPs (99 % in *M. galloprovincialis*, 76 % in *P. perna,)* and polyethylene the prevalent polymer. The FTIR analysis was conducted in attenuated total reflectance mode with air as background spectrum.	(Cozzolino et al., 2023)
	South Africa	PEST	1 mm–2 mm	52.11 MP/kg	Sediments	ATR-FTIR	Sediment MP levels were higher in winter compared to summer.	(Ariefdien et al., 2024)
	South Africa	PE and PS	≥1.0 mm	82 to 59 MP/g	Soft tissues of *Chiromantes eulimene, Austruca occidentalis,* and *Cerithidea decollata*	FT-IR	The three bioindicators exhibited MP bioaccumulation.	(Johnson et al., 2023)
	Senegal	–	<5 mm	945 607 MP km^{-2} and 159 g km^{-2}	Shelf waters	–	The mean abundance was around 258 954 MP particles per km2.	(Sonko et al., 2023)
	South Africa	PE and PS	≥1.0 mm	177 to 76 MP/L water	Estuarine surface water	FT-IR	–	(Johnson et al., 2023)
	South Africa	PP and PS	2–5 mm	16.13 particles kg^{-1} to 140.6 particles kg^{-1}	Sediments	Vibrational Platinum-ATR FT-IR	The average MP densities ranged from 25.3 particles kg−1 dwt to 140.6 particles kg−1. PP (31 %) and PS (30 %).	(Mutshekwa et al., 2023)
	South Africa	PE	0.5–1.0 mm	1587.50 ± 599.32 MP/kg	Sediment	FTIR-ATR	Fibres were the most dominant MP particle type.	(Apetogbor et al., 2023)
	South Africa	PE and PS	≥1.0 mm	99 to 82 MP/kg sediment	Sediment	FT-IR	–	(Johnson et al., 2023)
	South Africa	PE	0.5–1.0 mm	5.13 ± 6.62 MP/L	Water	FTIR-ATR	Fibres were the most dominant MP particle type.	(Apetogbor et al., 2023)

(*continued on next page*)

Table 1 (*continued*)

Continent	Country	Types of MP detected	MP Size	Abundance	Sample Matrix	Instrumental Analysis	Additional Information	References
	South Africa	PE and PP	<0.5	70.23 ± 7.36 MP/kg	Sediment	FTIR-ATR	The occurrence patterns of PE and PP were 46 % and 16 %, respectively.	(Samuels et al., 2024)
	South Africa	PEST	1 mm–2 mm	1.35 MP/g soft tissue wet weight	Biota: mussels, whelks and sea urchins	ATR-FTIR	Mussels had the highest level of MPs.	(Ariefdien et al., 2024)
	South Africa	PE		2.62 ± 0.41 MP/L	Water	FTIR-ATR	–	(Samuels et al., 2024)
	South Africa	Natural fibres	2 mm–5 mm in	185.07 ± 15.25 particles/kg	Sediment	ATR-FTIR	Transparent filaments were the most dominant MP shape for all samples.	(Julius et al., 2023)
	South Africa	PET	1 mm–2 mm	1.33 ± 0.15 particles/L	Water	ATR-FTIR	Black/grey filaments observed.	(Julius et al., 2023)
	South Africa	PEST	1 mm–2 mm	0.15 MP/L	Water	ATR-FTIR	MPs were identified based on their shape (fibres, fragments, spheres, filaments), colour (white, transparent, red, yellow, black, blue)	(Ariefdien et al., 2024)

polyamide (PA), polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), polytetrafluoroethylene (PTFE), rayon (RA), polyester (PEST), polyurethane (PU), silicone resin (SR), and chlorinated polyethylene (CPE), polyacrylamide (PAA), high-density polyethylene (HDPE), epoxy resin (ER), phenoxy resin (PR), Polymethyl methacrylate (PMMA), and polycarbonate (PC).

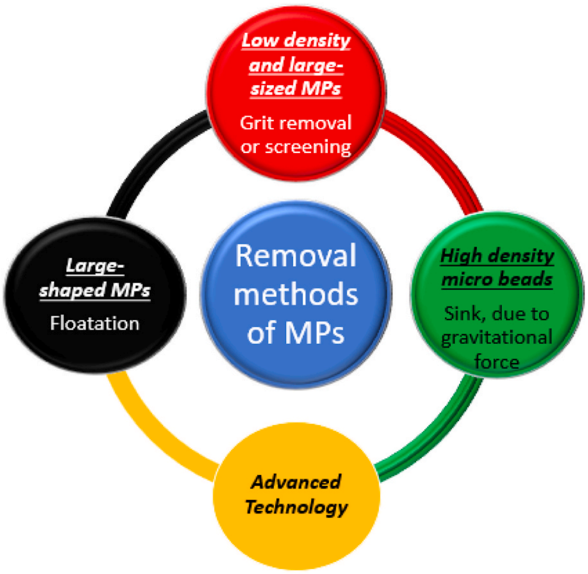

Fig. 5. Methods of removal of microplastics.

biomagnification along the food chain cannot be overemphasized. The outcome of the research work in Japan regarding the detection of MPs in dried fish consumed by the Japanese populace corroborates this fact [25]. Piyawardhana and co-authors detected polyethylene, polyethylene terephthalate, polystyrene, polyvinyl chloride, and polypropylene in the studied dried fish samples, with polyethylene having the highest percentage occurrence (35 %). Similar studies were conducted in Sri Lanka, China, Vietnam, South Korea, Taiwan, and Thailand and returned positive regarding the presence of MP in dried fish [25]. Microplastics, including polyethylene, silicone, polypropylene, and polyurethane, were also found enriched in some shorebirds' bodies on the Yellow Sea coast in China [33]. The presence of MPs in five tropical shark species in Malaysia, namely *Chiloscyllium punctatum, Carcharhinus sorrah, Carcharhinus dussumieri, Chiloscyllium hasseltii*, and *Scoliodon laticaudus* has recently further validated the fact that MPs indeed bioaccumulate along the food chain [34]. An abundance of 29.88 ± 2.34 items per Shark, with polyester having the highest occurrence frequency, was reported from the study. The presence of MPs has also been reported in East China's surface waters, with close to 94 % occurrence in all the sampling sites [19]. Like the result obtained by Matupang et al. [34], the dominant MP in the East China surface waters was polyester, accounting for 71.3 % of the total MPs detected [19]. Detailed information on rent detection of MPs in the Asian environment is provided in Table 1.

4. Recent occurrence pattern of microplastics in Africa

Data on the presence of MPs in African countries are relatively scarce, although their distribution within the continent (Africa) is not uniform. The surveyed literature in this study showed that more research on MPs was conducted in South Africa than in other African countries. These studies were carried out on both the biotic and abiotic components of the ecosystem, including sediments, soft tissues of selected organisms, shelf waters, and estuarine waters, to mention a few. For instance, Cozzolino and team members reported the presence of MPs in some mussel species (*Perna* and *Mytilus galloprovincialis*) within South Africa, ranging from 0.14 ± 0.19 to 0.21 ± 0.25 items/g [35]. Similarly, the soft tissues of *Chiromantes eulimene*, *Austruca occidentalis*, and *Cerithidea decollate* found in South Africa were observed to be bioaccumulated with 82 to 59 MP/g [36]. Also, recently in South Africa, Ariefdien et al. [37] reported that polyester (PEST) was found in mussels, whelks, and sea urchins with an abundance of 1.35 MP/g soft tissue wet weight, with the highest level of MPs in mussels.

In sediments, which are natural sinks for most pollutants, MPs have been reported to range from 16.13 particles kg^{-1} to 140.6 particles kg^{-1} using two South African recreational reservoirs as sampling sites [38]. Specifically, the types of MPs reported by Mutshekwa and colleagues are polypropylene and polystyrene, with percentage abundance of 31 % and 30 %, respectively. In a similar vein, Ariefdien et al. [37] investigated the presence of MPs in the sediments from South Africa and reported it to consist of 52.11 MP/kg. Furthermore, 70.23 ± 7.36 MP/kg in South African sediments were reported, with polyethylene and polypropylene having 46 % and 16 % occurrence patterns, respectively [6]. Of concern is the relatively high amount of MPs (1587.50 ± 599.32 MP/kg) in the South African sediments reported by Apetogbor and team members, with fibers being the dominant MP particle type found in the sediments [39]. Other recent articles on the presence of MPs in South African sediments have been published [36,40].

In water samples, precisely shelf waters in Senegal, the level of MPs was reported to be 945 607 MP km^{-2} and 159 g km^{-2}, while the mean abundance of MP was around 258 954 MP particles per km^2 [41]. This study, reported by Sonko and team members, is one of the few studies carried out concerning the presence of MPs in the Senegalese environments. Surprisingly, other recent studies on the aqueous ecosystem were reported on South African waters. One such study was conducted on estuarine surface water and reported MP levels ranged from 76 to 177 MP/L [36]. The levels of MPs reported by other Authors in South African waters are 1.33 ± 0.15 particles/L [40], 2.62 ± 0.41 MP/L [6] and 0.15 MP/L [37]. Additional information with respect to the recent detection of MPs in Africa is presented in Table 1. It is worth noting that of all MP types that have been reported to be present in the environment, polyethylene remains one of the most dominant. This observation is further supported by an earlier study stating that polyethylene is the most common source of waste in the environment [42]. To date, there are no regional programs covering the monitoring and control of MPs or transboundary MPs in a large number of African countries, as seen from the surveyed literature. Based on the data present on the levels of MPs in environment, it can be safely concluded that the ecosystem is at a risk of heavy MP pollution and hence requires remediation. Consequently, researchers are making continuous frantic efforts to remove MPs from both terrestial and aquatic ecosystem using diverse methods including floatation and advanced technologies. Scientists must take into consideration the use of green methods for this purpose to ensure that no more harm is caused during the remediation procedures.

5. Remediation strategies for the elimination of microplastics from the environment

Microplastics are reportedly present in high amounts in WWTPs via diverse channels such as industrial, domestic, and agricultural wastewater [18,43]. Consequent to the detection of a high number of MPs in WWTPs, quite a number of studies have investigated their behavior during the treatment process of WWTPs [44–46]. Based on the results obtained, it was discovered that the removal efficiency of the treatment process depended on the type of wastewater and technology employed. Microplastics of low density and large size are simply removed via physical treatment through specific processes, as summarized in Fig. 5. The physical treatment processes are targeted at removing large MPs and debris particles [44,45].

These processes include but are not limited to screening methods, grit removal, and sedimentation processes, which all take place in the primary clarifier [18]. Large-shaped MPs, including fragments and fibers, are removed by floatation. In contrast, high-density microbeads largely sink to the base of the sedimentation tank as a result of gravitational force. Additionally, smaller MPs are bound to microorganisms in the form of flocs [46]. These flocs are deposited in the secondary clarifier for biological treatment [16,46]. Further, some researchers have reported over 90 % removal efficiency of MPs by employing some advanced techniques such as rapid sand filtration, disc filtering, ozonation or dissolved air floatation, coupled with other processing methods [47,48]. However, some of these methods are expensive, thus researchers must continually work towards achieving better methods, which are cost-effective, that could removal a 100 % of MPs from WWTPs. It is important to state that Xu and colleagues in their analysis of MP ascertained a relationship between total phosphorus and small sized MP, ranging from 1 mm to 3 mm [10]. On the other hand, large-size MP (3 mm–5 mm) was related to total phosphorus and ammonia-nitrogen in the sample matrices analyzed [10]. Therefore, it is suggested that a method that would involve reducing these nutrients for effective removal of MPs be developed.

6. Ecotoxicity studies of microplastics

As much as the monitoring studies of MPs are important, so also are their ecotoxic impacts germane to ascertain the state of health of the environment. Most previous studies focused on the MPs levels in the aqueous environments and concluded that the treatment plants are a source of MPs in the aqueous environment [49,50]. However, scientists are currently making continuous and tireless efforts to investigate their diverse ecotoxic impacts, including their sources and fate, on the biotic components in the environment. These pollutants have the tendency to accumulate along the food web, making them lethal to humans and animals [51]. It is important to state that understanding the properties of pollutants is key in their fate determination. Meanwhile, there is not enough information on the characteristic features of MPs or their interaction patterns with other pollutants. Nevertheless, recent studies reported the behavior of MPs with respect to their adsorption or desorption prowess upon interaction with other pollutants [52,53]. Furthermore, the mechanism of uptake of MPs either by plants or animals is yet to be fully understood as well, although a recent study by Gan et al. [8] investigated the interaction between plants with MPs. Among the threats of MPs is recycled activated sludge, bearing in mind the wide use of sludge as fertilizer in agriculture [18]. More so, this sludge is used as a raw material for concrete, making the end-point of MPs the terrestrial environment [54].

Generally, ecotoxicity studies of pollutants are conducted using various model organisms [55–57]. Of all the bioindicators used for similar purposes, the *Corbicula fluminea* has been regarded as a great model for investigating the toxicity of microplastics and some other pollutants [58–60]. Guo and Feng, and other authors associated the vast usage of *Corbicula fluminea* with their tolerance and distribution pattern regarding diverse pollutants. For instance, Zhang et al. [61] reported that superoxide dismutase and catalase levels in *Corbicula fluminea* exposed to MP were elevated, which in turn indicates that an excess of reactive oxygen species (ROS) was produced. The species cause lipid peroxidation, harm mitochondrial and cellular components, and lower adenosine triphosphate levels [62]. These actions trigger apoptosis, which is mediated by the endoplasmic reticulum and mitochondria [62]. More details with respect to the functions of catalase and superoxide dismutase have been documented in the literature [63–65]. Similarly, findings on the toxicity of MPs showed that the bioconcentration of mercury was reduced by the uptake of the microplastics using the same *Corbicula fluminea* [66]. In the same vein, the uptake and/or adsorption of mercury by MPs was earlier reported by Turner and Holmes [67].

In all, it is safe to conclude that the presence of MPs in the environment could be more toxic than their pristine form as other pollutants get adsorbed to them. Moreover, this means that ingesting MPs by biotic components equates to consuming other pollutants, which is lethal. Furthermore, the metabolism of roxithromycin was used as an indicator to ascertain the toxicity of MPs after a two-week exposure using tilapia fish for the bioassay [68]. The cytochrome P450 enzymes showed significant variability in their activities, suggesting the impact of the presence of MPs on the metabolism of roxithromycin in the tilapia. However, relative to the lone exposure

Table 2
Ecotoxicity studies of microplastics.

Microplastics	Organisms	Maximum Concentration	Toxicity	Period of Exposure	References
Polystyrene	Asian seabass, *Lates calcarifer* frys	5 mg/L	Tissue lesions in gill, liver and intestine	15 days	(Sahabuddin et al., 2023)
Polymer not specified	Corbicula fluminea	640 mg/L	Imbalance in the antioxidant defense system of the clam, with increased levels of superoxide dismutase and catalase and decreased levels of glutathione peroxidase	4 days	(Zhang et al., 2023a)
MPs + microcystin	Corbicula fluminea	320 μg/L microcystin and 640 mg/L, respectively	Imbalance in the antioxidant defense system of the clam, with increased levels of superoxide dismutase and catalase and decreased levels of glutathione peroxidase	4 days	(Zhang et al., 2023a)
Not specified	Corbicula fluminea	0.13 mg/L	Decrease in filtration rate and increase in the level of lipid peroxidation, which indicated fitness reduction and lipid oxidative damage	8 and14 days	(Oliveira et al., 2018)
Microplastic + mercury	Corbicula fluminea	microplastics (0.13 mg/L) + mercury (30 μg/L)	Decrease in filtration rate and increase in the level of lipid peroxidation, which indicated fitness reduction and lipid oxidative damage	8 and14 days	(Oliveira et al., 2018)
polystyrene (32–40 μm diameters)	Juvenile Guppy (*Poecilia reticulata*)	100 μg/L and 1000 μg/L	MPs decreased the gut digestive enzymes activities; stimulation of the expression of gut immune response; induced gut microbiota dysbiosis.	28 days	(Huang et al., 2020)
Polystyrene	*Oreochromis niloticus*	100 μg L−1	Enhanced the bioaccumulation of roxithromycin in fish tissues	14 days	(Zhang et al., 2019)
Polystyrene + roxithromycin	*Oreochromis niloticus*	PS (100 μg L−1) + roxithromycin (50 μg L−1)	When compared to the lone-roxithromycin, the neurotoxicity it caused was alleviated due to the presence of PS	14 days	(Zhang et al., 2019)
Synthesized polyethylene MP fragments	Daphnia magna	5 mg/L	Reduction in algal feeding, body length, and the number of offspring. Higher accumulation of MP fragments likely resulted in higher mortality in the test organisms	21 days	(An et al., 2021)
Commercial polyethylene MP beads	Daphnia magna	5 mg/L	Lesser reduction in algal feeding, body length, and the number of offspring, as compared to the effect exerted by the MP fragments	21 days	(An et al., 2021)
Not specified	*Dicentrarchus labrax*	0.26 mg/L and 0.69 mg/L	Microplastic caused neurotoxicity via acetylcholinesterase inhibition, increased lipid oxidation in muscle and brain, and changes in the activities of the energy-related enzymes lactate dehydrogenase and isocitrate dehydrogenase	4 days	(Barboza et al., 2018)
MP + mercury	*Dicentrarchus labrax*	MP (0.26 mg/L and 0.69 mg/L) + Mercury (0.010 mg/L and 0.016 mg/L)	Non-monotonic responses of test organisms to mixtures. The mixture exerted significant inhibition of brain acetylcholinesterase activity and significant increase of lipid oxidation levels in brain and muscle	4 days	(Barboza et al., 2018)
Polystyrene	*Danio rerio*		Induction of inflammatory responses in fish liver. Significant changes in the lipid metabolites of triglycerides, choline, fatty acids, and phosphorylcholine which was an indication that lipid metabolism were disturbed in liver		(Lu et al., 2016)
Different compositions of MPs in Beach water samples, such as PE + PP; PE + PP + PS	Medaka larvae and juveniles	0.01, 0.1 and 1 % of MP weight/weight in fish food [the targeted concentrations for larvae were 3 μg L−1 e.g. 70 MPs·L−1 (0.01 %), 30 μg L−1 e.g. 700 MPs·L−1 (0.1 %) and 300 μg L−1 e.g. 7000 MPs·L−1 (1 %) of MPs and for juveniles, 1.5 μg L−1 e.g. 35 MPs·L−1 (0.012 %)]	Induction of sublethal effects on larval growth and behavior	30 days	(Pannetier et al., 2020)

to roxithromycin after two weeks, there was a significant increase in superoxide dismutase activity and a decrease in malondialdehyde contents when the fish livers were co-exposed to MPs and roxithromycin. This implies that oxidative damage was lessened in the fish liver after two weeks of co-exposure. The use of *Daphnia magna* has also revealed the toxicity of both small and large MPs, where individuals exposed to MP beads had a significantly higher survival rate than those exposed to small and large fragments of MPs [69]. From other surveyed literature works, ecotoxic impacts of MPs include, but are not limited to, abnormal swimming behavior, oxidative damage, changes in intestinal functions, immune responses, and lipid accumulation [70–72]. Other studies reported their cytotoxicity, cardiotoxicity, reproductive toxicity, and genotoxicity [21,73]. More detailed literature that has reported the ecotoxicity of MPs is given in Table 2. Based on the information obtained from previous works on the ecotoxicity of MPs, it can be observed that there is a scarcity of data on the chronic effects of MPs, taking into consideration the period these pollutants spend in the environment. This is a gap researchers should endeavor to fill in the near future.

7. Conclusion

Due to the fact that there is an increase in population the world over, the use of plastics in diverse sectors has become pronounced, hence the risk of MP pollution. The present study focused on a systematic appraisal of MPs, mainly on the Asian and African environments, with a primary focus on the most recent studies. It also summarized the trends in the methods for the environmental monitoring of MPs. From the data gathered, the two key instrumentations involved are the microscopes for visualization and the FT-IR for identification of the MPs. Based on the surveyed pieces of literature, China and South Africa have relatively more information on MP contamination in their countries. Meanwhile, studies on the MP contamination status should be cut across all countries; hence, this study becomes an eye-opener regarding the commencement of further research on the MP contamination of the environment. Furthermore, the ecotoxicity studies of MPs were investigated to ascertain the toxic nature of these compounds. This aspect of research is extremely key because it is pivotal concerning the remediation of these compounds. Microplastics have been declared toxic to biotic components, and all hands must be on deck to remove them from the environment continuously. Future research on the investigation of atmospheric MP transport is important, as it is an important delivery pathway with the deposition of MPs to ecologically relevant regions.

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Data will be made available on request.

CRediT authorship contribution statement

Elizabeth Oyinkansola Omotola: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Ganden Supriyanto:** Supervision, Investigation, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest.

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