Current status and trends of research on microplastic fugacity characteristics and pollution levels in mangrove wetlands

Bin Chen[1,2]*

[1]Key Laboratory of Estuarine Ecological Security and Environmental Health, Education Department of Fujian, Tan Kah Kee College, Xiamen University, Zhangzhou, China, [2]Department of Environmental Science and Engineering, Tan Kah Kee College, Xiamen University, Zhangzhou, China

Microplastics have been widely detected in the environment, while mangrove wetlands are considered barriers to land-based plastic transport to the ocean, requiring special attention. However, the current literature is distributed and broad besides limited information on the fate characteristics and pollution levels. This study uses a systematic literature review method to analyze the current research status and future trends. In this study, the literature is summarized and concluded that Characteristics including color, shape, size, polymer chemistry and surface microstructure are the basic information for microplastic research in mangrove wetlands. Size is the key to studying distribution and convergence without international standards. The shape is vital to study its sources and environmental processes. Color affects biological predation and is important information for studying ecological risk. The chemical composition of plastics is the key to studying microplastics' fingerprint information, source, and sink. The surface microstructure is an important basis for studying adsorption behavior and aging processes. Mangrove microplastic studies in China are mainly on the southern and southeastern coasts, and microplastic pollution is more severe in Fujian, Guangdong, and Guangxi than in Hainan. In contrast, studies on mangrove microplastics abroad are mainly concentrated in Southeast Asia, the Middle East, and South America. Overall, microplastic contamination was detected in the major distribution areas of mangroves worldwide and was correlated with mangrove density and human activities.

KEYWORDS

mangrove wetlands, research reviews, pollution levels, trends, environment, microplastic

Introduction

Plastics rapidly increase as man-made goods in the Anthropocene (Hardesty et al., 2017). The issues caused by the accumulation of improperly disposed plastic solid waste in marine and coastal zone environments due to their inability to degrade in the environment effectively is a major international concern (Lusher, 2015) (Plastic under

natural environmental conditions takes decades to centuries to completely degrade and disappear (Andrady, 2011). However, before disappearing, physical, chemical, and biological processes reduce the structural integrity of plastics, leading to their fragmentation (Browne et al., 2008). Internationally, plastics smaller than 5 mm are microplastics (Thompson et al., 2004; Hidalgo-Ruz et al., 2012). Microplastics have been widely detected in water, sediments, and other environmental media and organisms (Browne et al., 2011; Naji et al., 2017; Zuo et al., 2020). The amount of plastic and microplastics floating in the ocean is about 5.25 trillion pieces, equivalent to 65,269,000 tons (Eriksen et al., 2014). These particles exist throughout the Earth's ecosystems, including rivers, oceans, and mangrove wetlands. Because of their small size, microplastics can be ingested by various organisms, such as birds, mammals, and turtles, and fugacity has been detected from single cells in mammals (Stolte et al., 2015). More seriously, several problems have been reported in the metabolism of these organisms, such as microplastics blocking and scratching the digestive organs, leading to pseudo-satiety, reduced nutritional capacity, fertility and reproduction, induced organ wounds, rupture, and death (Maghsodian et al., 2021). Also, microplastics contain an average of 4% plastic additives, and such compounds may release toxic substances. In addition, microplastics in the environment can accumulate polycyclic aromatic hydrocarbons, polychlorinated biphenyls, and heavy metals, which can be enriched at higher trophic levels through the food chain, leading to the death of various marine organisms (Barnes et al., 2009; Teuten et al., 2009; Rios et al., 2010; Gallagher et al., 2016), and may pose human health and potential socioeconomic threats (Devriese et al., 2015; Leslie et al., 2017) (Browne et al., 2007; Thompson et al., 2004; Vethaak and Leslie, 2016).

To study microplastic fugacity characteristics and pollution levels, scientists usually collect samples from oceans, mangrove wetlands, and rivers (Claessens et al., 2011). Mangrove wetlands, as special habitats and important buffers, are considered barriers to land-based plastic transport to the ocean and require special attention for research. As a critical interface for river-to-ocean transport, mangrove wetlands play a vital role in trapping suspended matter in the water column and sediments while providing food and habitat for various marine and terrestrial organisms (J. Deng et al., 2020; Kathiresan, 2003). Mangroves reduce coastal erosion, act as filters for pollutants trapped in their sediments, and stop dispersing to open water (MacFarlane et al., 2007). According to a study on the distribution of microplastics in mangrove sediments, mangroves attenuate waves through strut roots, thereby affecting microplastic accumulation in sediments (Duan et al., 2021). Therefore, it is important to summarize the current study of the mechanism and relationship between microplastics and mangrove wetlands.

As one of the most important marine ecosystems, Mangrove ecosystems have sensitive and outstanding ecological values. Mangrove conservation and restoration are necessary to stabilize coastlines and maintain healthy coastal environments. Protecting and maintaining mangrove ecosystems for human benefit has also become a "biodiversity hotspot" for various species. Studies have shown that most of the solid waste polluting mangroves is plastic, textiles, glass, and wood, with plastic accounting for about 70% of the total (van Bijsterveldt et al., 2021). The high fertility of mangrove wetlands leads to a different mechanism of microplastic decomposition than other habitats such as aquatic environments (Li et al., 2019). Mangroves prevent erosion by stabilizing sediments, maintaining water clarity, absorbing large amounts of CO_2, filtering pollutants, and capturing sediments from land, as evidenced by the important contribution of organic carbon (Meynecke et al., 2007), especially the ecological function of mangrove carbon sinks to mitigate global climate change (Donato et al., 2011). Pollution from plastic waste has been reported to pose a serious threat to mangrove vegetation height and density (J. Deng et al., 2020). Over the last few decades, mangroves have been subjected to multiple threats and are disappearing worldwide at an alarming rate of 1–2% per year. (Richards and Friess, 2016). However, the current literature is distributed and broad besides limited information on the fate characteristics and pollution levels of microplastics in mangrove ecosystems. Literature reviews are necessary to summarize the research status and trends.

Literature reviews occupy a fundamental position in scientific research and serve as a bridge to thematic studies. This is because any study is based on the contributions of previous authors. A review of prior contributions in the field before conducting a study on a particular topic is not only a way to respect previous authors' contributions but also a way to illustrate the innovation through comparison. Studies addressing microplastic fugacity characteristics and pollution levels in mangrove ecosystems are relatively limited (J. Deng et al., 2020). Based on the important ecological value of mangrove wetlands and the increasing threat of microplastics, further research related to mangrove microplastics needs to be sorted out and summarized to draw the attention of more scholars. In this paper, a systematic literature review was conducted to review the characteristics of microplastics in mangrove wetlands and their pollution levels at home and abroad. The objectives are: 1) To summarize the overall characteristics of microplastics, including color, shape, size, polymer chemistry, and surface microstructure. 2) To summarize the global and Chinese mangrove microplastic pollution levels and distribution information. 3) Suggest future research directions.

The next section 2 discusses the study background and research methodology while section 3 focuses on the study results. The section 4 presents manuscript discussion, conclusion and future study suggestions.
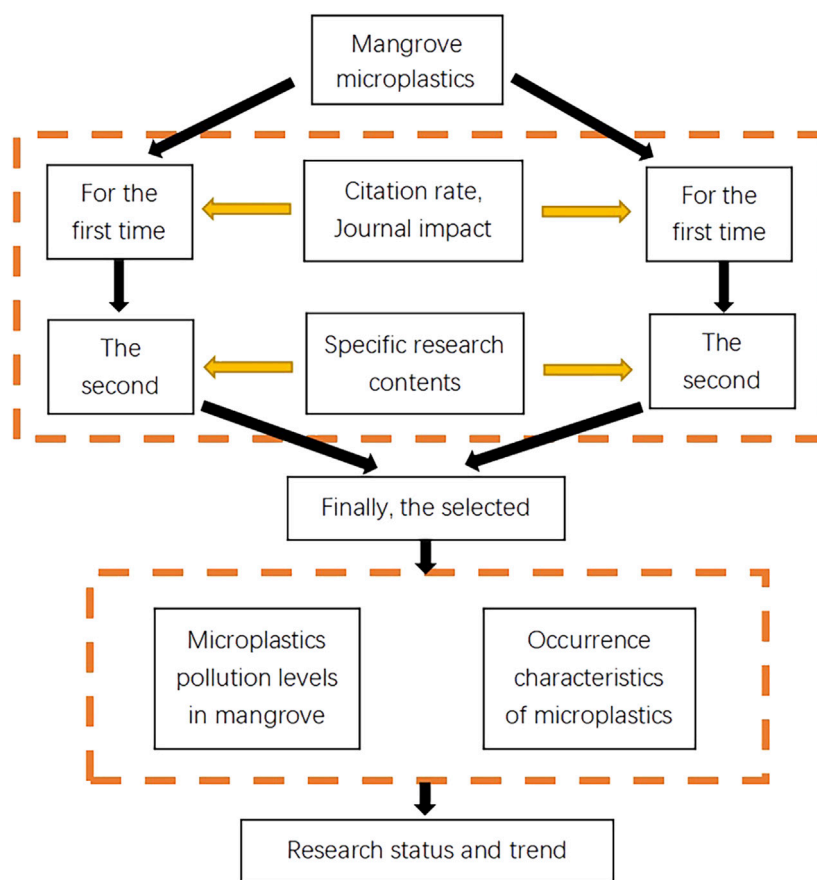
FIGURE 1
Flowchart of analysis by systematic literature review method.

Materials and methods

Literature reviews are divided into "narrative literature reviews" and "systematic literature reviews" (Petticrew, 2001). The Systematic Review Methodology (SRM) is a standardized literature research method that utilizes different databases and multiple search and analysis techniques to comprehensively capture research progress on a topic and draw conclusions accurately. The systematic literature review method ensures clarity in all processes, from identifying literature selection criteria to the specific selection of literature, especially the distillation of findings from the scattered research literature. It is a transparent mechanism for literature review research (Borenstein et al., 2021). This paper systematically analyzed the related literature through the systematic literature review method with the following flowchart and determination criteria (Figure 1).

The data used in this paper were all obtained from the China National Knowledge Internet (CNKI) and Web of Science (WOS). In CNKI, the Chinese words "microplastics + mangroves" were used as the keyword for the subject search from 2006-01-01 to 2021-12-31. In WOS, the core collection database was searched with "microplastic mangrove" as the keyword for 2006-01-01 to 2021-12-31. In addition, to cover the research papers as much as possible, terms such as plastics deris, plastics pellets, sediment, and wetland were used to supplement the search, and the content ranking was verified manually.

Results and discussion

The systematic literature review method was used to summarize the characteristics of microplastic fugacity in mangrove ecosystems from the literature, including color, size, composition, surface microstructure, *etc.*;
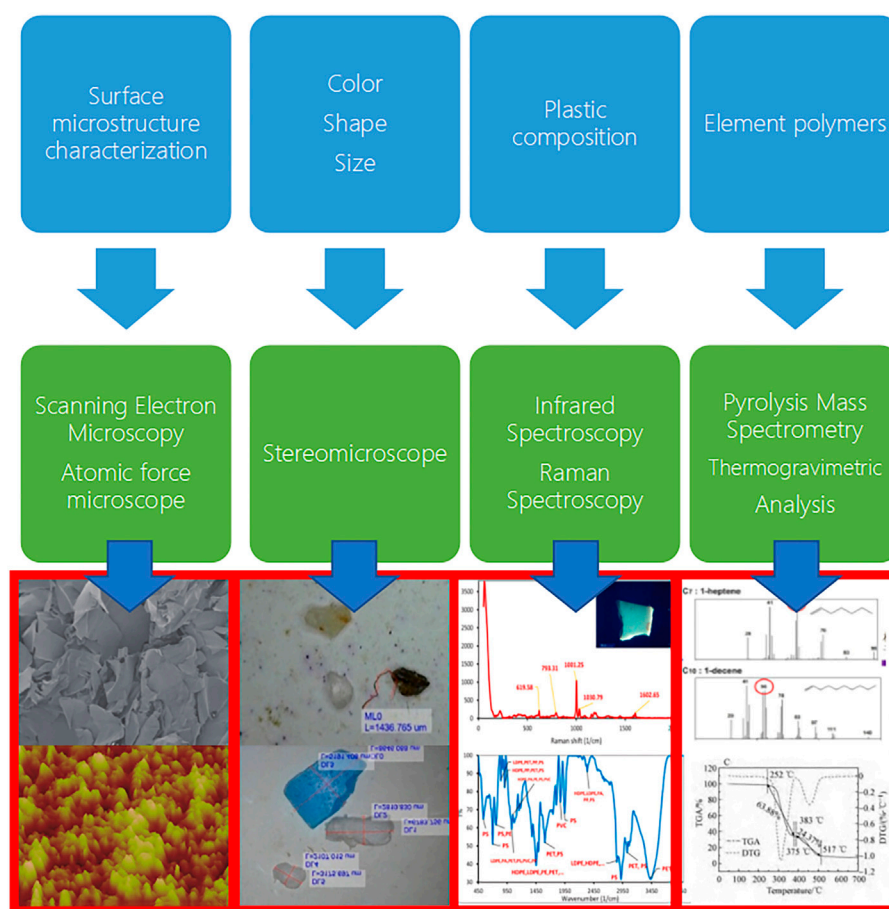
FIGURE 2
Illustration of microplastic fugacity characteristics and identification methods.

to summarize the level of microplastic pollution in mangrove wetlands at home and abroad; and then to speculate future research trends.

Fugacity characteristics as basic information for microplastic research in mangrove ecosystems

Microplastic abundance is the main feature to describe the pollution level of the mangrove ecosystem in terms of unit quantity. In addition, microplastic fate characteristics include their physical and chemical properties, and the latter has become important basic information for microplastic studies in mangrove ecosystems. Many scholars use the fugacity characteristics of microplastics to infer their sources, analyze environmental processes, and assess ecological risks (Peng et al., 2017). Characteristics, such as their size, color, shape, composition, surface microstructure, and other properties, have been explored in various reports (Figure 2). Usually,

physical identification methods use microscopic identification, divided into three parameters: size, color, and shape (Frias et al., 2018). Furthermore, infrared spectroscopy (μ-FTIR), fourier transform reflectance infrared spectroscopy (ATR-FTIR), micro-Raman spectroscopy (μ-Raman), pyrolysis-gas chromatography-mass spectrometry (Py-GCMS) and thermogravimetric analysis (TGA) are used to identify different elements and polymers of microplastics. Some scholars also observed their microstructure by scanning electron microscopy (SEM) and atomic force microscopy (AFM) to study their aging process and environmental behaviors.

Microplastic particles' abundance, distribution, and fate are influenced by their size (Duan et al., 2020). It has been reported that the smaller plastic particles are, the more frequent they occur in sediments (Batel et al., 2018). Studies have shown that smaller microplastics in mangrove sediments may pose a greater potential threat to biological communities because smaller microplastics are more likely to adsorb persistent organic pollutants (POPs) and are more readily transferred to

organisms. Therefore, it is necessary to study the size of microplastics. However, there is no international standard for sizing microplastics in mangrove ecosystems. Even in the more mature marine plastic litter research field, there is still no internationally accepted classification standard for marine microplastics. However, marine litter can be classified according to size.

Based on a review of the relevant literature, the most widely accepted definition of "microplastics" is those with the longest diameter of less than 5 mm (Hidalgo-Ruz et al., 2012). Some scholars have simply divided them into large microplastic particles (1–5 mm) and small microplastic particles (0.1–1000 μm) (Imhof et al., 2012; Qiu et al., 2016). Some researchers have considered further subdivisions of plastic particles. For example, the Marine Litter Technical Group for the implementation of the Marine Strategy Framework Directive (MSFD) recommends further subdivision into large microplastics (1–5 mm), medium-sized microplastics (5–25 mm), and giant microplastics (>25 mm), while those that are not visible to the naked eye (<1000 μm) are called "small microplastics" (Galgani et al., 2013). Gigault et al. (2018) classify microplastics larger than 2.5 cm as giant microplastics. Particles with a size of 0.5–2.5 cm are called medium-sized microplastics, while particles with a size of 0.5–1 mm are called large microplastics, and particles with a size of 0.001–0.5 mm are called small microplastics. Nano plastics in this classification are the last group with dimensions of 1 nm–1 μm (Gigault et al., 2018). In another study on the microplastics collected from the Atlantic, sizes were classified into five groups: 0.25–0.5 mm, 0.5–0.75 mm, 0.75–1 mm, 1–2 mm, and 2–5 mm (La Daana et al., 2017). Maghsodian et al. (2021) classified plastic particles found in mangrove sediments into three groups based on size: microplastics >2.5 cm, medium-sized plastics of 0.5–2.5 cm, and microplastics of 0.5–3 mm (Maghsodian et al., 2021). Combining the above literature on microplastic and microplastic size classification, this paper summarizes them into six groups for reference.

There have been many studies on the size characteristics of microplastics from environmental media and organisms in mangrove ecosystems. In terms of environmental media, the main studies have been on mangrove sediments; for example, microplastics smaller than 20 μm have been found in Singapore mangrove sediments (Nor and Obbard, 2014). Naji et al. (2019) classified microplastics isolated from mangrove sediments of Ramsar (Iran) into two groups (10–300 μm and 300–1000 μm) based on size, with small particles accounting for 70–97% (Naji et al., 2019). Zhou et al. (2020) reported the highest percentage of particles below 2.5 mm in size in a study of microplastics in mangrove sediments along the southeast coast of China (Zhou et al., 2020). Microplastics, mainly smaller than 1 mm were detected in the mangrove sediments of the Maowei Sea (J. Li et al., 2018). The above studies indicate that smaller sizes mainly dominate microplastics in mangrove sediment.

Among the reported microplastic characteristics of organisms in mangrove ecosystems, a study on the size of microplastics in crab and fish in mangroves in Beibu Bay, China, showed that 1–500 μm accounted for 85.84% (Zhang et al., 2021). Maghsodian et al. (2021) observed microplastics of size 0.5–3 mm in mudskippers (Maghsodian et al., 2021). Smaller microplastic sizes were reported in a study on the quantification and characterization of microplastics ingested by juvenile fish associated with mangroves in KwaZulu-Natal, South Africa, with an average microplastic size of 0.77 ± 0.89 μm (R. Naidoo, 2020).

Microplastic shape and environmental processes

There is no official unified naming standard or specification for microplastic shapes (Gago et al., 2019). The detection of different shapes of microplastics may be due to different pollution sources or different environmental processes (e.g., erosion, solar radiation, biodegradation). Microplastics can take regular and irregular shapes. Regular shapes are usually from direct release (primary microplastics) and are generally beads or small balls. At the same time, irregular shapes are mainly due to the decomposition of larger plastic fragments (secondary microplastics), which contain fibers, debris, and other irregular shapes (Khatmullina and Isachenko, 2017). Based on various literature reports, microplastic shape characteristics were divided into six groups (Figure 3). The first group is irregularly shaped, coarse-edged, sharp microplastics called fragments, which are the most abundant. The second group is like movie film, transparent, thin, and flexible, called film-like. The third category is round, irregular particles and larger than other microplastics. The fourth category is also round particles, more regular and about 1 mm in size, but less diverse than the third category. The fifth category is elongated, called fibrous, and comes in various sizes, with a relatively high percentage as granular. The sixth category is foam-like, formed by the fragmentation of polystyrene foam (Pflieger et al., 2017).

The main shapes of microplastics observed in marine organisms are fibrous or granular, which may come from discarded fishing gear (Zhang et al., 2021). The shape of microplastics in the aquatic environment can be regular or irregular and indirectly affect their environmental processes. For example, when microplastics are in the form of fibers or films, they are more buoyant, difficult to settle in the water, and more likely to spread to different marine areas, so more organisms may mistakenly ingest them as food. On the other hand, when microplastics are present as spheres, they are relatively easier to settle or precipitate (Jung et al., 2021).
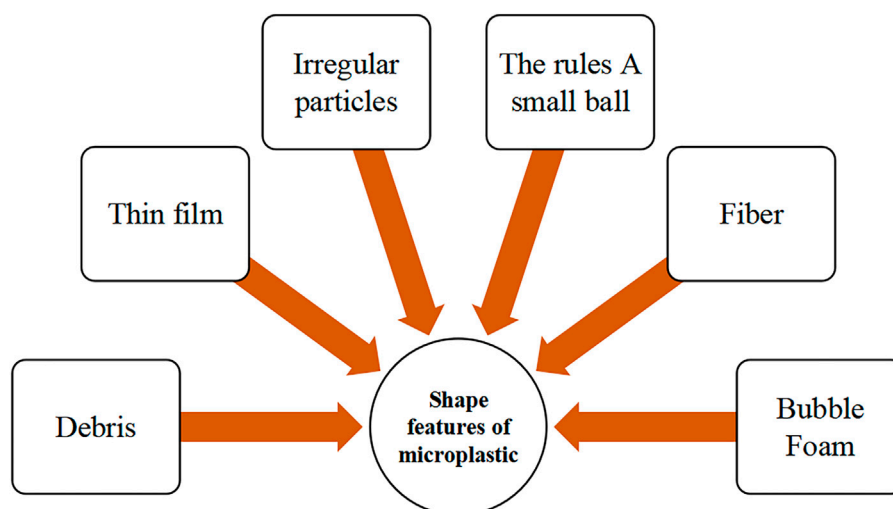
FIGURE 3
Classification diagram of microplastic shape characteristics.

For the shape characteristics of microplastics in mangrove sediments, domestic and foreign scholars have also done a lot of research. Domestically, the highest percentage of microplastics in the Pearl River Estuary, China mangrove sediments was found in particles and fibers (Zuo et al., 2020). Most microplastics detected in Beibu Bay, China mangrove forests were also particles and fibers (Zhang et al., 2021). In another study on mangrove microplastics in Dongzhai Harbor, Hainan, four types of microplastics were detected: elastic fibers, soft films, foams, and fragments, among which elastic fibers (EF) were detected at a high level in all the study areas, accounting for 57.02%, followed by films accounting for 21.11%. Microplastics detected in mangroves of Qinzhou Bay, Guangxi were fragmented, fibrous, and spherical. It was found that the highest percentage of isolated microplastics in mangrove sediments and fish in southern Iran was fibers (Maghsodian et al., 2021). Particles and fibers were the most abundant microplastics detected in the north coast of the Persian Gulf (Naji et al., 2019). In the study of mangrove microplastics in the Colombian Caribbean Sea, particles, fibers, and film forms were the most common (Garcés-Ordóñez et al., 2019). Fibrous microplastics were mainly detected in mangrove sediments from Ramsar (Iran), where sewage discharge may be the main source (Naji et al., 2019). Synthetic resinous material was detected in all seven habitats of Singapore mangroves, and most microplastics were fibrous (Nor and Obbard, 2014). The fibrous shape was the most commonly isolated in mangrove microplastic studies. This may be because this morphology is more likely to be enriched in organic matter-rich mangrove sediments by adsorption (Zhou et al., 2020).

Microplastic color and biological predation

Color is one of the physical characteristics influencing microplastic feeding by organisms at different trophic levels (John et al., 2021). Microplastics vary in color and look similar to plankton. Some of the most important commercial fish and their larvae are visual predators that may ingest more prey-like microplastics, such as white, brown, and yellow plastics (Maghsodian et al., 2021). Another study showed that dark-colored microplastics (such as black and blue) were ingested more by organisms than light-colored microplastics due to their attractiveness or color similarity to prey (John et al., 2021).

In studies of mangroves in the Persian Gulf, the highest proportion of white microplastics was found in sediments, probably due to secondary microplastic degradation (Naji et al., 2019). The proportion of microplastics in particles isolated from seafood such as fish is highest in black (60%) and lowest in white (7%) (Maghsodian et al., 2021). The most common microplastic particles observed in a study of juvenile mangrove fish in KwaZulu-Natal, South Africa were blue (Naidoo et al., 2020). Blue, black and white microplastics are most common on the northern coast of the Persian Gulf (Naji et al., 2019). Transparent white, black and blue are the three main colors of microplastics observed in mangroves in southern China (Li et al., 2019). The microplastics detected in Qinzhou Bay in Guangxi have a variety of colors, such as white, transparent, yellow, green, red, and blue. Combined with the above reports, the most common colors identified in the mangrove include black, blue, white, transparent, red, green, *etc.* (Frias et al., 2018). However, the isolation and identification of microplastics cannot

TABLE 1 Classification and application of typical plastics.

Plastic properties	Plastic-type	Abbreviation	Application
Thermoplastics	Polystyrene	PS	industrial accessories, egg protection packaging, aquaculture floating balls, disposable tableware
	Polyvinyl chloride	PVC	building materials, cosmetics, transparent food packaging, water pipes
	Low-density polyethylene	LDPE	plastic wrap, cable cover and plastic film
	High-density polyethylene	HDPE	food, cleaning products and cosmetics, insulation shed
	Polyethylene	PE	containers, food packaging and industrial accessories
	Polyamide	PA	Nylon textiles and industrial accessories
	Polypropylene	PP	Agricultural ropes and fishing nets, industrial accessories and knitwear
	Polycarbonates	PC	baby bottles, glass assembly industry, automotive industry, electronic appliances industry accessories
	Polyethylene Terephthalate	PET	beverage bottles, mineral water and polyester for clothing
Thermosetting plastics	Epoxy resin	EP	coatings, insulation materials and adhesives

be based solely on color differences. Because color discrimination is subjective, the visual identification of microplastics is highly controversial. Some particles are white, which is very different from transparent particles. The difference between white and transparent particles is their turbidity. Transparent particles are completely colorless, high transparency. White microplastics are opaque, as opposed to transparent particles. Further evaluation is needed to determine whether it is the original color or discoloration caused by environmental processes such as UV from sunlight and whether it is primary or secondary plastic (Frias et al., 2018; Khan et al., 2021a; Khan et al., 2021b). The usefulness of the green approach has ensured sustainable economic and environmental performance (Naseem et al., 2021; Sarfraz et al., 2022a; Ivascu et al., 2022).

The chemical composition of plastics and fingerprint information

Synthetic resins are plastics' major components and determine the microplastics' chemical structure or properties (John et al., 2021). Plastics are macromolecules synthesized by addition polymerization or condensation polymerization of monomers as raw materials, as shown in Table 1. Plastic is commonly divided into thermoplastic and thermosetting plastic; the distinction depends on whether to melt when heated. Epoxy and phenolic resins are thermosetting plastics, while polyethylene, polypropylene, polystyrene, and polyvinyl chloride are thermoplastic polymers. Most household plastics are thermoplastics. According to previous statistics, about 90% of global plastic production is thermoplastic polymers (Antony and Neal., 2009).

The physical properties of plastics and non-plastics make microplastics accurately identifiable. In addition to visual recognition, other, more precise methods are needed to identify microplastics. According to the literature, infrared spectroscopy and Raman spectroscopy are widely accepted methods to identify different polymer types of microplastics (Maghsodian et al., 2021; Pan and Chen, 2021; Khan et al., 2022). The analysis of microplastic polymer is the main basis for determining its origin. For example, when PP, PE, or PS are the main polymers, most of the detected microplastics are generated from the fragmentation of larger plastic products (Eerkes-Medrano et al., 2015; Sarfraz et al., 2022b; Mohsin et al., 2022).

PET was more abundant than other polymers in a study of microplastic fugacity characteristics in Brazilian mangroves. In a study of Indonesian mangrove sediments, 50% of the isolated microplastics were PS, and the other 50% were PE and PP (Cordova et al., 2021). PE and PP were detected in mangrove sediments in Singapore, with the highest levels of PA and PVC microplastics (Nor and Obbard, 2014). The most abundant polymers found in mangrove Vietnam was PE (Khuyen et al., 2021). PS, PE, PP, and PET are almost the most abundant microplastics in Iran's Persian Gulf (Maghsodian et al., 2021). The abundance of PP, PA, and PS is higher than in other polymers in the Colombian Caribbean (Garcés-Ordóñez et al., 2019). The highest abundance of PE and PP was found in the port of Kingston (Rose & Webber, 2019). PE and PP were detected more frequently than other polymers in four estuaries on the east coast of South Africa (Govender et al., 2020). In the study of African mangrove fishes, the percentage of isolated microplastics were PP (70.4%), PET (10.4%), PA (5.2%), and PVC (3.0%) (Naidoo et al., 2020).

Three major microplastics, PS, PP, and PE, were detected in the Qinzhou Bay, Guangxi mangrove forests. In the survey of mangrove sediment in the Pearl River Estuary, PE and PP had the highest abundance among the polymers (Zuo et al., 2020). PE and PET were most abundant in the mangrove forests of Zhanjiang, Guangdong Province, China (Huang et al., 2020). Mangrove sediments in Beibu Gulf, China, had the highest abundance of PE and PET (Zhang et al., 2021). Microplastics

in mangroves of Maowei Sea, South China Sea area were mainly PE, PP, and PS. Overall, thermoplastic microplastics were detected more frequently, and PE and PP were the most frequently detected microplastics in mangrove sediments along the Chinese coast (Zuo et al., 2020).

Microplastic surface microstructure, adsorption behavior, and aging process

High temperatures and strong solar UV light can accelerate plastic fragmentation (Lambert et al., 2013). Microplastic particles may bind and integrate into aggregated material with other organic fragments (Rillig, 2018). During cracking, the surface morphology of plastic particles may change significantly due to corrosion and biological effects (Imhof et al., 2012). Roughness and cracks may appear on the surface of the microplastic, while clay minerals and quartz particles can be embedded in the pores or cracks of the microplastic (Kowalski et al., 2016). Environmental erosion and biofouling can significantly alter the surface morphology of plastic particles, which may show roughness and cracks (Imhof et al., 2012).

Further, inorganic and organic substances may enrich and alter the overall morphological characteristics of microplastics (Kowalski et al., 2016). Naji et al. (2019) used scanning electron microscopy to isolate some non-plastic particles from suspected plastic-like particles in mangrove sediments (Naji et al., 2019). Electron microscopy scanning is a common method to identify microplastics indicating microstructure, and some scholars have also used atomic force microscopy to observe their surface roughness change process (Qian Zhou, 2021).

Pollution levels and distribution of microplastic in mangrove wetlands

The spatial distribution of microplastics can provide important clues to the location of plastic release (Heo et al., 2013; Lee et al., 2013). In recent years, microplastic pollution in mangrove wetlands has been rising, and their pollution levels are significantly different from other coastal environments due to their unique ecological characteristics. Investigations of mangrove microplastics may significantly change our estimates of plastic stocks in the marine environment (Nor and Obbard, 2014). However, systematic investigation of the microplastic distribution and pollution assessment in mangrove wetlands are limited (Li et al., 2019). Based on the existing literature reports, the following summarizes the microplastic pollution levels in mangrove wetlands from domestic and international dimensions.

Distribution of microplastic pollution in mangrove wetlands of China

From the analysis of microplastic pollution levels in the Chinese mangrove distribution map (Hu L et al., 2020), it can be summarized that current studies mainly focus on microplastic pollution in mangrove sediments, and the study areas are mainly concentrated in South China and Southeast coast (Figure 4). Deng et al. (2020) studied mangrove forests in the Jinjiang estuary, Fujian Province. They found that the overall abundance of microplastics in sediments was high, ranging from 980 ± 255 to 2340 ± 188 n/kg (H. Deng et al., 2021). Zuo et al. (2020) investigated microplastic contamination in sediments from three mangrove areas in the Pearl River Estuary, Guangdong Province. They found that microplastic abundances ranged from 100–7900 n/kg with a mean value of 851 ± 177 n/kg (Zuo et al., 2020). The microplastics' mass concentrations in Dongzhai Harbor, Hainan mangrove sediments ranged from 1.39 to 13.65 mg/kg. The concentration of microplastics in mangrove forest sediments outside Qinzhou Bay, Guangxi, ranged from 306–6168 n/kg, with an average concentration of 2174.5 ± 2206.8 n/kg. In contrast, the abundance of microplastics in the sediments inside the mangrove forest was much lower, with an average concentration of 42.9 ± 26.8 n/kg. This may be related to the transport hindrance of plastic waste by the dense aerial root system of mangroves and tides (Li et al., 2018). In a study of mangrove microplastics in coastal mangroves in southeast China, an average of 5738.3 ± 8.3 n/kg microplastic particles were detected in mangrove sediments (Zhou et al., 2020). An average of 15 ± 12.85 n/kg of microplastics in sediment was found in the sandy mangrove coast (Li et al., 2018). Current studies and trends show that investigating microplastic pollution in intertidal mangrove wetlands is receiving more and more attention from scholars. Li et al. (2019) suspected that microplastic mangrove pollution in the semi-enclosed sea is significantly different from other coastal types due to its unique geographical characteristics and found that the abundance of microplastics in mangroves of the Maowei Sea estuary was much lower than that in the ocean entry zone, with abundances ranging from 520 ± 8 to 940 ± 17 n/kg (Li et al., 2019). However, data on microplastic distribution and fugacity characteristics in mangrove sediments from semi-enclosed seas are still very limited. On the whole, microplastic pollution in Fujian, Guangdong, and Guangxi provinces' mangroves is somewhat more serious than that in Hainan. The average number of plastic particles isolated from mangrove sediments in southern China was 851 ± 177 n/kg (Zuo et al., 2020).

Pollution levels of microplastics in mangrove wetlands abroad

From the map in Figure 5, it can be seen that global mangrove forests are mainly distributed in tropical and subtropical regions. Since the data of the global mangrove microplastic system study
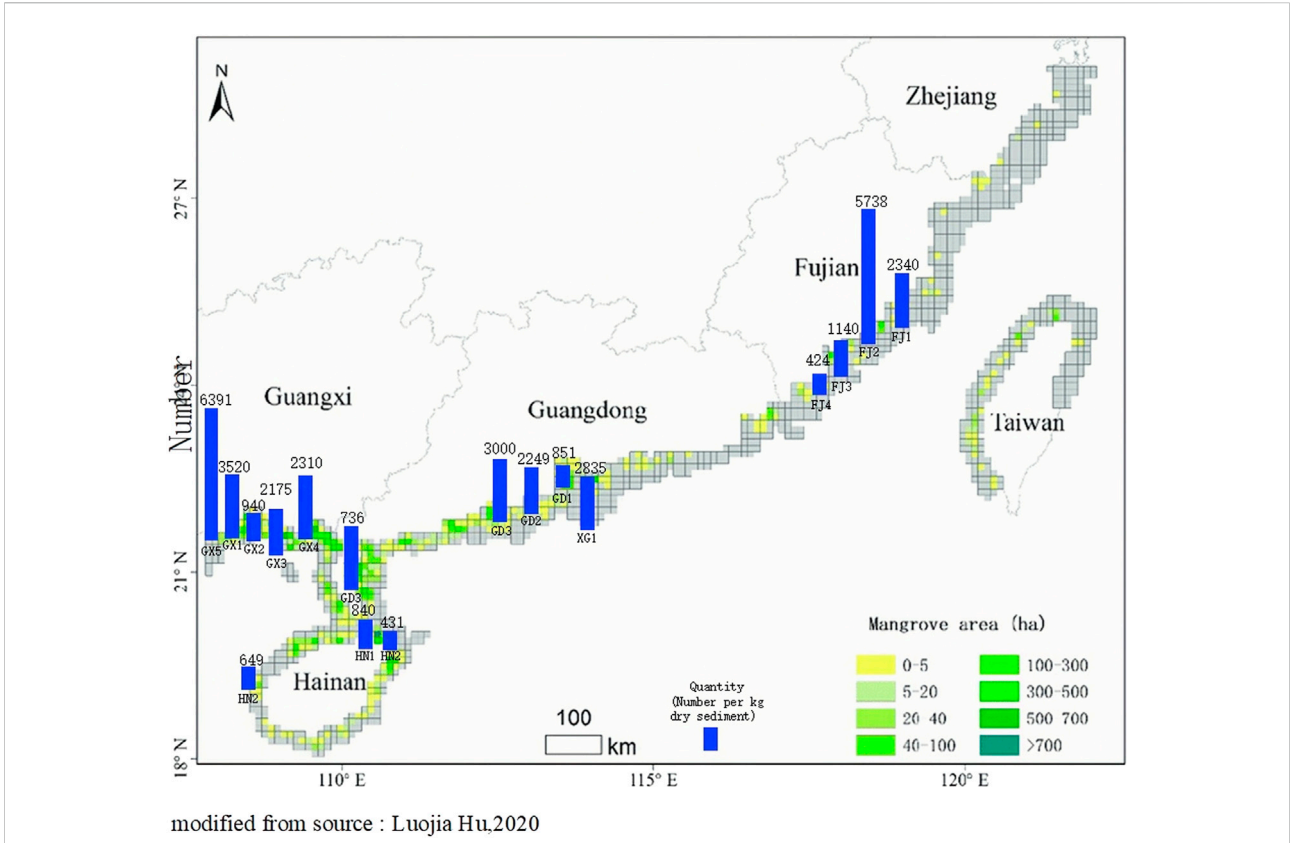
FIGURE 4
Distribution of microplastic pollution in mangrove wetlands of China.
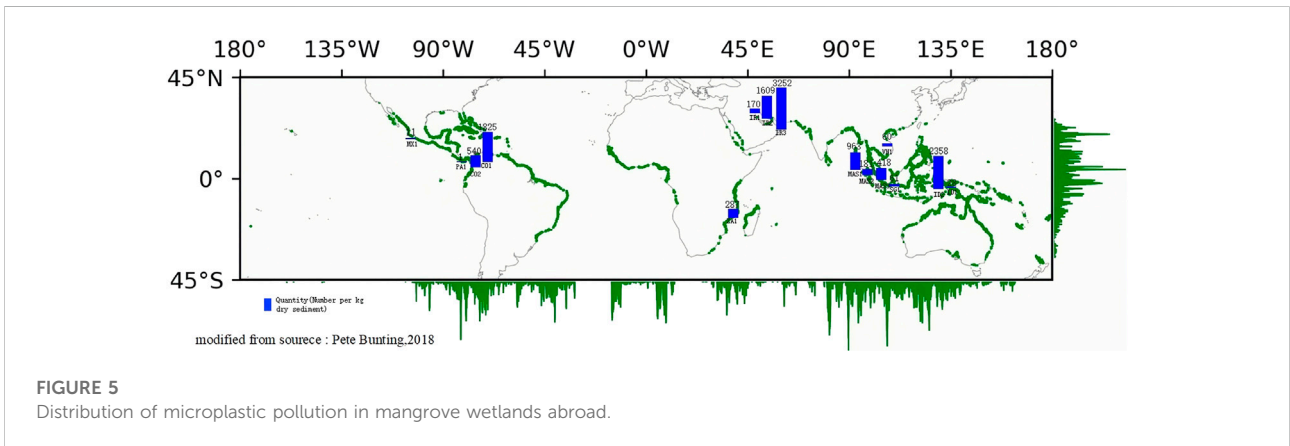

FIGURE 5
Distribution of microplastic pollution in mangrove wetlands abroad.

is not comprehensive, some of the research data are listed in this paper. Figure 5 shows that the investigated regions are mainly concentrated in Southeast Asia, the Middle East, and South America. Barasarathi et al. (2014) conducted a study in Kapar, a remote area in Malaysia far from human industrial and commercial activities. They found that this region's abundance of microplastics

in the surface sample of mangrove sediment (50 cm × 50 cm, depth 5 cm) was 418 n/kg. The microplastics were mainly distributed on the surface 1–2 cm depth (Barasarathi et al., 2014). Smith (2012) Smith (2012) found an abundance of 3349 n/kg of microplastics in mangrove sediments from Motupore Island, Papua New Guinea. Nor and Obbard (2014) investigated microplastic abundance in

mangrove wetlands in Singapore and found an overall abundance range of 12.0–62.7 n/kg (dry weight) (Nor & Obbard, 2014). The average microplastics in mangrove sediments from Ramsar (Iran) ranged from 19.5 to 34.5 n/kg of dry sediment, respectively (Naji et al., 2019). However, the total number of microplastic particles found in mangrove sediments in southern Iran was 2657n (Maghsodian et al., 2021). Microplastic contamination was detected in both seawater and sediments of mangroves in South Africa (Govender et al., 2020). In another study, the average amount of microplastics isolated from mangrove sediments in the northern Persian Gulf was 34.5 ± 19.5 n/kg (Naji et al., 2019). Areas with lower microplastic contamination indicate lower anthropogenic activity, and areas with higher anthropogenic activity may generate more plastic solid waste, resulting in higher abundance levels of microplastics (Nor and Obbard, 2014).

Overall, no matter whether in China or abroad, microplastic contamination was detected in all major mangrove distribution areas and correlated with mangrove density and human activities. As an important coastal zone special habitat, mangrove wetlands are an important interface for sea-land transport and an important barrier to blocking land-based inputs of plastic pollution. Mangrove wetlands provide a habitat for a variety of organisms and also contain significant carbon sinks. Microplastic pollution poses a significant ecological risk and potential threat to human health and social and economic development (Browne et al., 2007; Devriese et al., 2015; Thompson et al., 2004; Vethaak and Leslie, 2016). Microplastic pollution and distribution in mangrove wetlands is attracting increasing scholarly attention (Zhang et al., 2021).

Future studies should focus on the microplastic transport process, ecological risk assessments, the effects on the carbon cycle, and policies and management plans for microplastic pollution.

Discussion and conclusion

In this paper, we systematically reviewed the published articles on mangrove-related microplastics. Microplastic fugacity characteristics are the basis for studying mangrove ecosystems, which include color, shape, size, and polymer, based on physical sensory identification, chemical composition analysis, and electron microscopic micrographs. The size of microplastics is the key to studying the distribution and convergence, but there is no internationally accepted classification standard, and this paper summarizes them into six groups (Table 2). The microplastics in mangrove sediments are relatively small in size, and those detected in organisms are also mainly small in size. The shape of microplastics is the key to studying their origin and environmental processes. Generally, the shape of primary microplastics is relatively regular, and the shape of secondary microplastics is influenced by environmental processes and plastic raw material types. Most scholars agree to describe the shape

TABLE 2 Microplastic size classification grouping.

No	Size range	Major category	Minor category
1	>2.5 cm	Microplastics	Giant microplastics
2	0.5 cm–2.5 cm		Medium-sized microplastics
3	1 mm–5 mm	microplastics	Large microplastics
4	0.5 mm–1 mm		medium-sized microplastics
5	0.001 mm–0.5 mm		Small microplastics
6	1 nm–1 μm		nanoplastics

characteristics of microplastics by six categories (Figure 3), such as fragments, films, and fibers. The fibrous shape is the most commonly isolated in mangrove microplastic studies (Zhou et al., 2020). Microplastic color affects biological predation and is important information for studying ecological risk, which may be related to biological feeding behavior and microplastic attachment. However, environmental influences may alter microplastic color. Further assessment is needed to determine whether it is the original color or environmental processes that bring about the discoloration and whether it is primary or secondary plastic (Frias et al., 2018).

Infrared and Raman spectroscopy are recognized methods for detecting different polymer types of microplastics and are key to studying microplastic fingerprint information and source sinks (Maghsodian et al., 2021). Overall, thermoplastic microplastics were detected more frequently, and PS, PP, and PE had the highest frequency of microplastic detection in Chinese coastal mangrove sediments (Zhou et al., 2020). The surface microstructure of microplastics is an important basis for studying adsorption behavior and aging processes and is generally observed using scanning electron microscopy. Microplastic studies in China are mainly on southern and southeastern mangrove coasts, and pollution is more serious in Fujian, Guangdong, and Guangxi than in Hainan. Studies on mangrove microplastics abroad are mainly concentrated in Southeast Asia, the Middle East, and South America. Overall, microplastic contamination was detected in the major distribution areas of mangroves worldwide and was correlated with mangrove density and human activities. Although this study may not be rigorous enough due to the limited data, microplastic research in mangrove wetlands has attracted increasing attention from scholars (Zhang et al., 2021).

Study recommendations

Based on the above summary of the microplastic fugacity characteristics and pollution distribution in mangrove wetlands, this paper then proposes several suggestions for future research trends: 1) To study the microplastic transport process from land-based sources to the ocean from the perspective of microplastic environmental behavior, and the mechanism of microplastic blockage

by mangrove wetlands. *2)* Strengthen the census of mangrove microplastics and pollution source analysis, and systematically study the spatial and temporal distribution characteristics, fingerprint information, and influencing factors of global microplastics. *3)* Study the effects of microplastic pollution on different mangrove forest species, tree ages, growth and development, and mortality, as well as the effects on various organisms and communities inhabiting the forest, and then comprehensively assess the ecological risks induced by them from macroscopic and microscopic perspectives. *4)* To study the effects of microplastics on the role of various microorganisms and algae and the carbon cycle in mangrove wetlands from the perspective of carbon neutrality and the ecological value of abundant mangroves. *5)* Finally, policies for microplastic pollution in mangrove wetlands and integrated management of plastic throughout its life cycle are proposed based on the above studies.

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Conflict of interest

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