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Pollution of Freshwater Ecosystems by Microplastics: A Short Review on Degradation, Distribution, and Interaction with Aquatic Biota

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Abstract: Plastic pollution of freshwater environments, particularly microplastic (MP), is a global ecological issue of growing scientific concern. This has sparked a flurry of studies on the presence of MP, its interactions with chemical pollutants, its uptake by aquatic species, and the ensuing (bad) impact. The primary objective of this article is to 1) show the distribution of MPs in freshwater environments, 2) display the interactions between MPs and heavy metals in freshwater ecosystems, and 3) to summarize the existing literature on MPs uptake by aquatic organisms and their impacts.
Keywords: Microplastics; aquatic organism; Freshwater ecosystems; ecotoxicological impacts; heavy metals

1. Introduction

Plastic is widely produced and utilized across the world owing to its durability, flexibility, lightweight, low cost, and waterproof bulk [1]. Plastic manufacturing has risen year after year, and the annual worldwide plastic output was over 322 million tonnes in 2016. It is expected that output would climb to 33 billion tonnes by 2050 [2]. Despite the availability of many hundreds of polymers, the most regularly used polymers, polyethylene (PE), polystyrene (PS), polyvinylchloride (PVC), polyamide (PA), polypropylene (PP), and polyethylene terephthalate (PET), have all been investigated for negative effects. Due to the wide distribution and mismanagement of plastic waste, it has become a global problem. Recently, the coronavirus (Covid-19) pandemic has caused a rapid surge in plastic waste goods such as masks, gloves, and shopping bags [3,4]. Over time, plastics have accumulated in the terrestrial environment and are finally deposited in the aquatic environment [5]. Plastic waste can be spread into aquatic systems through direct discharge from land sources and it has been estimated that 80% of aquatic waste is transported by waste disposal, tourism, industrial activities, waste runoff, and wastewater treatment plants also constitute one of the dominant sources of microplastic pollution in freshwater aquatic systems [4].

Due to the high resistance and inert maturity of plastics [6], which lead to slow degradation and a long half-life under environmental conditions [7], they can persist in aquatic systems for up to 50 years after having been released, and they might take hundreds or thousands of years for all plastics to mineralize [8]. Plastics degrade and fragment in the environment, reducing their size and producing a proliferation of microscopic particles known as microplastics (MPs) and nanoplastics (NPs). These small plastic particles are a serious problem for aquatic systems for both ecological and economic reasons, they reduce the aesthetic value of water environments [5], and MPs pose threats to aquatic biota biodiversity due to their ease of ingestion. MPs can adsorb water hydrophobic pollutants and heavy metals and desorb them into habitats [9]. Therefore, MPs act as carriers of different chemicals that can be additives or pollutants and transfer them to living biota upon ingestion [10]. Chemical concentrations in MPs may be 10-100 times greater than in the surrounding environment [11]. These dangerous compounds have the potential to bioaccumulate not only in aquatic biota but also in humans [12].

Despite substantial studies about MP contamination in marine environments, monitoring of MPs in freshwater has received little attention [13]. Therefore, this review highlights:

- Previous studies regarding MPs degradation and distribution in freshwater ecosystems.
- Ingestion of MPs by aquatic biota.
- The effects of functional feeding guilds on microplastic accumulation in different organisms.

2. Plastic wastes degradation

The fundamental problem with plastic garbage is that it does not dissolve naturally like other organic materials but is constantly damaged and fragmented by environmental variables such as abiotic and biotic stimuli. The broken plastic particles reduced in size over time, eventually reaching micro- and nanoscale sizes. Plastics are categorized according to their size into macroplastics (> 25 mm), mesoplastics (5 - 25 mm), big microplastics (1 > 5 mm), and nanoplastics (<1.0 µm) after decomposition. Photo, thermal, chemical, and mechanical fragmentation are all examples of the abiotic breakdown of plastic waste [14]. Photodegradation, on the other hand, is the most prevalent non-biodegradation mechanism for MP fragments exposed to sunlight [15]. Under the action of sunlight, (typically UV) and temperature, photosensitive components within the plastic polymer chain react with light, producing chain scission and a relative molecular mass decrease, leading to MP degradation [16]. Most MPs' C-C and C-H bonds are specifically broken by UV radiation at wavelengths of 290-440 nm in the sunshine [17]. Photodegradation causes embrittlement, cracking, and weakening of the plastic over time, releasing more free radicals and hastening the aging of MPs [18]. Although photodegradation can disrupt the polymer's backbone, bacteria can only degrade oligomers [19].

The thermal degradation of MPs is like photodegradation in that the chain polymer is broken to create free radicals after absorbing enough heat [14]. Heat degrades the surface mechanical characteristics of plastic polymers, fractures C-C bonds, overcomes bond dissociation energy, and causes thermal deterioration [17]. Mechanical forces (such as wind, sand, and waves) are principally responsible for MP fragmentation, which causes embrittlement and, as a result, a loss of mechanical stability [14].

Yet, biological interactions with plastic trash play a crucial part in its breakdown. Long polymer chains might be broken by microorganisms found in natural habitats such as bacteria, fungi, algae, and others [20]. The two most common biodegradation mechanisms are biophysical degradation and biochemical degradation. Microorganisms initially cling to the polymer surface for biophysical degradation, influencing the polymer's physical phenomena, surface structure, and porosity. As microbes attack a polymer, it separates into oligomeric pieces by hydrolysis, ionization, or protonation. Enzymes released by fungi or bacteria break down non-water-soluble polymers into pieces for biochemical breakdown [21]. The functional groups, relative molecular mass, and surface characteristics of MPs such as hydrophobicity and adhesion are dramatically altered by microbes [22]. Moreover, enzymes and biological free radicals damage MPs and plastic additives, causing embrittlement and mechanical instability [23]. As a result, both abiotic and biotic processes are major drivers of aging plastic breakdown, resulting in micro- and nano-plastics that can harm human health and all other living species. Every change in plastic size modifies the hydrophobicity of the surfaces of MPs, hence affecting their adsorption ability toward environmental pollutants [24, 25].

MPs come in a variety of forms and compositions, and they were divided into primary and secondary groups according to their source. Primary MPs are produced in extremely small quantities for specific uses such as lotions, toothpaste, and similar chemicals that may enter the freshwater of a defective wastewater treatment plant (WWTP) [26]. Moreover, fibers, which are emitted into wastewater by washing machines, account for most primary MPs [27]. Despite this, one of the most significant sources of primary MPs was industrial activity, which ranged from the fabrication of air-plastic media to the construction of boat nulls [26]. Secondary MPs are large plastics such as fragments and films, produced when larger plastics are exposed to degradation.

3. Distribution of microplastics in different freshwater environments

A high number of reviewed studies collected samples from surface water or from sediment of water bodies. A few studies sampled both from the water bodies. MP pollution varies widely, with environmental [28] and anthropogenic [29] variables governing their prevalence and abundance. Environmental characteristics, rather than human ones, may have a significant impact on the spread of MPs [30]. Environmental factors that impact the incidence and quantity of microplastics include winds, wave motion, hurricanes, and hydrodynamic direction [31]. On the other hand, anthropogenic variables, such as population density, area urbanization, and economic growth, are linked to MP contamination in the aquatic system. The quantity of MPs present in a freshwater environment is affected not only by environmental and human variables, but also by the size of the water body, the kind of waste management utilized, and the amount of sewage overflow [32]. The vertical distribution pattern of MPs in various freshwater systems is determined by particle properties such as density and size [33]. Plastic density influences organic material partitioning and contamination in surface water, water column, and sediment [4,34]. Polymers with densities greater than that of water are thought to be deposited in aquatic system sediment. Moreover, low-density polymers sink because of biofouling by microorganisms. MP concentrations in sediments can be many times greater than those in surrounding water due to biological activity [36].

The concentration of MPs in freshwater systems worldwide ranges from 0 to several million particles per cubic meter [37]. These variations might be attributed to factors such as sample, location, natural circumstances, and analytical techniques [33]. Rivers are recognized to play a significant role in the transmission of plastic garbage into lakes, seas, and oceans [38]. According to Lebreton et al. [39], the amount of plastic now entering the seas via riverine systems is between 1.15 and 2.41 million tonnes per year. Asian rivers make up 86% of the total world intake, whereas European rivers account for only 0.28%.

Despite the relatively large number of studies demonstrating MP abundance in freshwater systems all over the world, providing conclusions on MP distributions in global rivers remains difficult because most research investigated MPs only in one specific compartment, such as the water phase, riverbed, or shoreline, and few studies included results on MP concentration both in water and sediment phase [30,33]. Moreover, most studies analyzed MP concentrations using various units of measurement depending on the use of diverse sampling methods and experimental designs.

4. Interaction between heavy metals and MPs:

Metal pollution occurs naturally in the environment and is caused by a variety of human causes, including industrial discharges, metal extraction, and electronic trash [40]. Widespread pollutants in the environment lead to the continual entrance of heavy metals into aquatic ecosystems through urban wastewater, sewage effluents, and agricultural runoff [41]. Despite being inert, plastic has been shown to have a significant affinity for heavy metals [42]. Some studies have recorded the presence of metals in MPs collected from different aquatic environments [43].

These metals can be associated with plastics during plastics manufacture as metal additives to improve their properties or because of the adsorption of metals that exist in aquatic environments [44]. The association of metals with MPs was studied mainly in the marine system. Ashton et al. [45] reported that the most frequent metals in MPs taken from beach sediments on the English coast, sediments and saltwater off the coast of Egypt [46], and in the Persian Gulf in Iran [47] were Al, Fe, Sn, Mn, or Cr. Moreover, more dangerous elements such as Pb and As, as well as Zn and Cu, which are poisonous only in high quantities, have been detected at numerous places along the Chinese and Mediterranean Sea coasts [48]. Moreover, Liu et al. [49] discovered median concentrations of Fe (302 mg/kg), Zn (19.6 mg/kg), Mn (18.6 mg/kg), Cu (0.89 mg/kg), and Ni (0.15 mg/kg) on MPs in Hong Kong's sandy beaches.

According to Deng et al. [50], the adsorption of metals on MPs occurs in three phases. The first stage involves the fast interaction of heavy metal ions with active sites on the surface of MPs particles, which is primarily governed by covalent and Van der Waals forces. As heavy metal adsorption on MP particles reaches saturation, the second step of adsorption occurs, and the heavy metal begins to slowly diffuse into the pores of the MP particles. The adsorption rate falls in the third stage, finally reaching an equilibrium condition between adsorption and desorption.

The adsorption capacity of MPs to metals depends on the polymer type. Each polymer has its own physical and chemical characteristics such as size, crystallinity, age, polarity, and surface functional groups that may influence its adsorption behavior during the adsorption process [51]. It has been reported that aged MPs have a greater potential for metal adsorption than virgin MPs. The increase in metal adsorption on aged MPs is due to surface changes caused by the influence of weathering and ultraviolet radiation [43]. These changes enhance the surface area and create anionic sites for metal adsorption [43]. Moreover, Acosta-Coley et al. [11] discovered that heavy metal redistribution and concentrations on MP particles are affected by degradation processes and that secondary plastic particles had greater detectable concentrations of heavy metal (28 metals) than white pristine plastic particles (7 metals).

Nevertheless, various environmental conditions, including temperature, pH, salinity, and dissolved organic matter, may alter metal adsorption on MPs [52]. The effect of pH and salinity on MP adsorption capacity varies depending on the metal [53]. Dissolved organic matter can reduce MP sorption capacity by diminishing accessible sorption areas or interacting with contaminants desorbed on the MP surface [42].

Biotic and abiotic components in the aquatic ecosystem are dynamically interacting, therefore it is very important to elucidate the biological factors that influence the adsorption of heavy metals by MPs. Microorganisms in aquatic settings are diverse and play a significant role in many biogeochemical processes [54]. Their presence complicates the relationships between MPs and heavy metals since MPs might create emergent ecological niches for microorganisms through microbial biofilm development [55]. Microbial biofilm is one of the major biological elements that impact the adsorption of chemical contaminants, including heavy metals, by modifying the physical and chemical characteristics of the MP surface [56]. Environmental variables may have an indirect impact on the biofilm structures that grow on the MP surface. According to Chen et al. [57], pH, nutritional salts, and nitrogen have a stronger influence on colony shape than MP particle size. As a result, pollutant adsorption and desorption from MPs are processes that might increase MP toxicity [52].

5. Ingestion and accumulation of plastic particles by aquatic biota:

Plastic particle concentrations in aquatic habitats have been shown to impact aquatic creatures such as freshwater invertebrates, oysters, lugworms, and fish [58-60]. Plastic particles' number, size, density, and color are the primary variables that make them accessible to aquatic organisms [61]. Small particles are easily ingested and accumulated in organisms [62]. One reason for small size selectivity may be due to the organism’s mouth capacity and body size [63]. It is not only plastic size but also the presence of microorganisms on plastic particles (biofouling) that attracts aquatic biota to ingest them [64]. Therefore, a study revealed that the guts of various aquatic organisms at nearly every trophic level contained plastic particles [65]. After seven days of exposure, zebrafish (Danio rerio), a freshwater species, accumulated plastic particles (5 µm in diameter) in its gills, liver, and gut, resulting in various observable consequences such as inflammation, lipid buildup in the liver, and alterations in metabolic profiles [66]. MPs were shown to be consumed by a variety of freshwater macroinvertebrates, including Gastropoda [67] and Oligochaeta [68].

It is well known that aquatic insects constitute a variety of taxonomic groups that spend at least one life stage in the aquatic environment and exist in rivers, lakes, streams, and oceans [69]. These organisms exhibit a wide range of morphological, behavioral, and physiological characteristics [70]. They contribute to nutrient cycling through the partition leaves, littering organic particles, preying on other insects and tiny fish, and serving as food sources for other invertebrates and vertebrates [71]. Much research has been conducted to better understand the relationship between plastics and aquatic insects. More than twelve species of aquatic insects colonized plastic sheets floating in mid-water in England, according to Macan and Kitching [72]. Since 2018, there has been an increase in research on the relationship between plastic particles and aquatic insects, which may be classified as environmental monitoring, field experiments, and ecotoxicological bioassays [73]. Originally, most field investigations concentrated on macro- and mega-plastics, establishing the significance of plastic particle debris as an extra substrate for oviposition by some aquatic insects [74]. Since 2013, the researcher’s attention has been directed to the smaller plastic particles (micro-nano) because of their smaller size, they can be easily dispersed and become abundant in the aquatic environment [74].

Most of the insect publications regarding environmental monitoring (29 studies reported by [74]) investigated one order of the insect (Diptera), and the remaining ones studied three or more orders. There are over twelve families in the order Diptera.

The Chironomidae were the most examined family, while Chironomus was the most studied genus. Chironomus larvae are the most common members of mud communities in ponds and lakes, and their behavior is extensively documented [75]. Different studies were undertaken to investigate the effect of feeding behavior on MP ingestion in different trophic guilds such as collector-gatherers (Chironomus sp. and Siphonurus sp.) and predators (Lestes virdis) [68,76]. According to Bertoli et al. [77], collector-gatherers accumulate much more MP than other functional feeding guilds. Nevertheless, no difference was seen between the various functional habit groups. Previous investigations [68,76] required more than one person to achieve adequate mass for the assessment of MP contamination in the whole-body organism due to the tiny size of some insects. A few studies looked at MPs in specific organs (Malpighian tubes), which are thought to be the organ of choice for MP bioaccumulation in Culex pipiens [78]. However, many researchers have reported the biomagnification of MPs in the gastrointestinal tract in a variety of fish and other species higher up the food chain.

The ability of aquatic insects to uptake MPs depends on several factors such as MP abundance, size of particles, and other factors related to the morphological, physiological, and behavioral characteristics of the organisms [79]. Also, Scherer et al. [80] reported that the high availability of natural food items decreases the ingestion of MPs. This fact was confirmed by Fueser et al. [81] where the larvae of Chironomus tiberius ingested more plastic particles when the larvae were starved. The previous study demonstrated the importance of natural food sources; when the food supply becomes scarce, organism selectivity decreases, and more plastic particles are ingested. Immerschitt and Martens [82] recorded that dragonfly nymphs (Lepidoptera sp.) can fragment large plastic particles and resulting in the degradation of mesoplastics into microplastics, consequently, it increases the abundance of smaller particles making them easier to ingest by other organisms [83] and then transfers through the food web [84]. Furthermore, Ehlers et al. [85] demonstrated that caddisfly larvae (Lepidostoma basale) not only ingest MP particles but also use them for building their shelters together with stone and sand particles.

6. Impact and ecotoxicology of MPs

Microplastics have a negative influence on the aquatic ecosystem's ecological functions by influencing organic phenomena, modifying natural habitats, interfering with the bacterial population, and disrupting species events [86]. For example, the presence of microplastics may reduce algae's chlorophyll content and, as a result, their photosynthetic efficiency, causing growth inhibition [87]. The inhibition of algae formation reduced the biomass of primary producers in the aquatic environment, which most likely had a negative impact on secondary producers in the nutrient cycle [88].

Current research aims to investigate the impact of various forms of MP intake on freshwater species. Since invertebrates account for up to 90% of fish prey biomass, the effects of MP absorption by freshwater benthos are significant [89, 90]. Most laboratory investigations have employed fragment forms, followed by spheres or pellets, with very little study utilizing fibers [73]. The impacts of these laboratory experiments are more visible in the early stages of development [91]. They found that the presence of microspheres and pieces in the sediment had a negative impact on the growth and emergence of Chironomus tepperi and Chironomus riparius [92]. The unfavorable effects were substantially associated with the size, amount, and type of polymer consumed [91]. During laboratory chronic exposure, pellets of (PVC), (PET), (PS), and (PA) demonstrated various unfavorable effects, including morphological deformities in the mandibles, mentum elongation, and wing spreading. Chironomus riparius was found to be mortal and to have a longer developing and emerging period [93]. Nevertheless, no harmful effects were reported on the same species' larvae after acute exposure (26-100 mg/h, 48 h) [94]. Furthermore, Ehlers et al. [85] reported that the stability of caddisfly larvae decreases with increasing content of plastic particles (PVC and PET) in the shelter, implying that MPs may endanger caddisfly because the stability of the shelter is reduced, resulting in a reduction in protective function and the larvae being more vulnerable to predation. Also, because plastic is lighter than sand, the chances of the shelter being carried by water currents may rise.

It is crucial to highlight that if the insect individual cannot rid itself of MPs during the ecdysis phase, the MPs will remain with it for the duration of its ontogenetic development [74]. This bioaccumulation resulted in biomagnification due to particle transfer up the trophic chain via predation [95].

In terms of the influence of MPs on cellular organization levels, Shaha and Pandit [96] conducted just one investigation on aquatic insect larvae (Chironomus circumdatus). MPs increased peroxidation levels, suggesting oxidative damage, lowered the antioxidant defense system, and changed gene expression, according to the researchers.

Heavy metals interacting with MPs may be another method for generating harmful effects, particularly when consumed by aquatic creatures [97]. Several investigations have shown that MP and heavy metals are prevalent in fish bodies [98]. Positive connections between MPs intake and heavy metals have been discovered in several aquatic species. As they enter the bodies of both animals and people, they may have an effect on the immune system and cause various illnesses [49]. Additionally, the existence of biofilms on the surfaces of MPs constitutes another issue, as the MPs become a cocktail of various chemicals, heavy metals, and dangerous bacteria. Its overall exposure differs significantly from that of its constituent components, resulting in complex difficulties [99]. Feng et al. [100] discovered that pathogenic bacterial populations on MP surfaces, such as Erythrobacteriaceae, Xanthobacteriaceae, and Vibrio, might enhance the environmental toxicity of MPs in the marine aquaculture business. Although the potential risk of MPs as pollutant transporters are unclear, it is hypothesized that simultaneous exposure to MPs, heavy metals, and microorganisms might amplify the negative effects and produce unanticipated harm to the biosphere. As a result, several topics are proposed to address the gaps in knowing the toxicity of cumulative exposure to MPs and other heavy metals in freshwater biota.

7. Conclusion

As discussed earlier, microplastics usually result from the decomposition of huge plastic particles into microscale plastic particles that spread throughout our freshwater and terrestrial environments. Furthermore, data on microplastics in Africa is extremely limited compared to our knowledge of the worldwide situation. This is due to the small focus from governments and researchers on the difficulty of microplastics in Africa until late 2019 and 2020. Also, this is often due to the problem of precisely measuring microplastic concentrations. When microplastic concentrations rise, other materials such as sediments or meteorological factors such as rainy seasons reduce their abundance, as reported in many places. However, other studies suggest that these correlations aren't very certain, and more work must be done to review the important factors that affect the concentrations of microplastics in the environment. The concentration of microplastics in living organisms is one of the most important indicators of microplastic pollution and its penetration into our food systems. High concentrations of living organisms, including insects and worms, were reported in South Africa and Egypt [102, 103]. The concentrations are around 291 particles per gram of the wet weight of those insects. Also, high concentrations of sediments were found within the same areas, with an average concentration reaching around 8000 particles per kg dry weight. The very best concentration of microplastics in an aquatic organism, globally, was found in Egyptian fish, with a degree of 7000 particles/fish [101]. Most of the places where these samples were taken were heavily populated areas, and microfibers were the most prevalent components of plastic pollution recorded within the samples taken from different places in Africa, especially polyethylene and polypropylene. Even though most microplastic research has focused on marine life, it has been highlighted that water bodies in Africa require more attention since they receive the drainage and trash of inhabitants in their catchments.

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