pollutants

Review

Microplastics in the Aquatic Environment—The Occurrence, Sources, Ecological Impacts, Fate, and Remediation Challenges

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Citation: Chaukura, N.; Kefeni, K.K.; Chikurunhe, I.; Nyambiya, I.; Gwenzi, W.; Moyo, W.; Nkambule, T.T.I.; Mamba, B.B.; Abulude, F.O. Microplastics in the Aquatic Environment—The Occurrence, Sources, Ecological Impacts, Fate, and Remediation Challenges. *Pollutants* **2021**, *1*, 95–118. https://doi.org/10.3390/pollutants1020009

Academic Editor: Paolo Pastorino

Received: 19 April 2021
Accepted: 16 June 2021
Published: 18 June 2021

Abstract: Microplastics are discharged into the environment through human activities and are persistent in the environment. With the prevalent use of plastic-based personal protective equipment in the prevention of the spread of the COVID-19 virus, the concentration of microplastics in the environment is envisaged to increase. Potential ecological and health risks emanate from their potential to adsorb and transport toxic chemicals, and ease of absorption into the cells of living organisms and interfering with physiological processes. This review (1) discusses sources and pathways through which microplastics enter the environment, (2) evaluates the fate and behavior of microplastics, (3) discusses microplastics in African aquatic systems, and (4) identifies research gaps and recommends remediation strategies. Importantly, while there is significant microplastics pollution in the aquatic environment, pollution in terrestrial systems are not widely studied. Besides, there is a dearth of information on microplastics in African aquatic systems. The paper recommends that the governments and non-governmental organizations should fund research to address knowledge gaps, which include: (1) the environmental fate of microplastics, (2) conducting toxicological studies under environmentally relevant conditions, (3) investigating toxicity mechanisms to biota, and developing mitigation measures to safeguard human health, and (4) investigating pollutants transported by microplastics. Moreover, regulatory measures, along with the circular economy strategies, may help reduce microplastic pollution.

Keywords: contamination; degradation; plastics; water pollution

1. Introduction

Global plastics production surged from 1.5 to 245 megaton in the period 1950 to 2008 with a small decrease to 230 megaton in 2009 [1,2]. Annual plastic production gives an indication of how much plastic waste ends up in the environment as microplastics. About 10–15% of all plastic manufactured each year end up as municipal solid waste, which is cause for concern [3]. Plastics are laden with additives, such as fillers, plasticizers, colorants, lubricants, stabilizers, that enhance their properties [3–6]. For instance, plasticizers constitute 70% of the weight of plastics, while 3% are endocrine chemicals such as bisphenols and flame retardants [7].

The bulk of plastic waste entering the marine environment originates from terrestrial sources. Transportation mechanisms involved include (1) street litter is mobilized into waterways by rain, and wind, (2) improper or illegal dumping of waste, (3) inappropriately covered waste containers and vehicles, (4) badly managed dump sites, (5) plastic manufacturing and processing amenities, (6) sewage treatment and sewer overflows, (7) recreation and fishing activities, and (8) solid waste disposal facilities by the seashore [8]. About 80% of the production of plastics that wind up in marine environments originates from run-flow water from land waters to wastewater treatment plants (WWTPs) [9]. Numerous studies have shown that plastic debris constitutes a considerable proportion of waste around marine environments, while data on the extent of pollution in freshwater environments is gradually building up [10–15]. This debris contributes to the microplastic load within the environment. Other sources of microplastics are (1) personal care products, where they are deliberately introduced for their exfoliating properties in toothpaste, shower gels and soaps [16,17], and (2) industrial processes such as air blasting, which require the abrasive action of microplastics [18,19].

Microplastics, or microbeads, are plastic particles < 5 mm diameter, and they include nano-sized particles (1 nm) [20,21]. Their size has been miniaturized or fragmented enough that there might be a need for the use of microscopy techniques to study them [22,23]. In many cases, microplastics continue to carry the chemical structure of their parent plastic with minimum alterations due to exposure to varied environments [24]. When these microplastics are ingested by aquatic life, they bioaccumulate and pose a serious challenge to the food chain, and are consequently a danger to human health [25,26]. In general, chemical pollutants are known to bio-magnify up the food chain [27]. Microplastics when not removed by conventional water treatment processes, are small enough to be easily ingested and can be absorbed into the tissue of invertebrates [28]. They cause pathological and oxidative stress, reproductive impediments, interference with enzyme activity, and stunted growth [29]. Research has reported microplastics even in fiber form in the gut of aquatic animals, from where they can be consumed by humans [22,30,31]. For example, zooplanktons eat microplastics instead of algae, and small teleost eats zooplankton and indirectly consume microplastics [32]. Generally, plastics adsorb and hyper-concentrate a wide range of chemicals called persistent bio-accumulative and toxic chemicals including pesticides, flame retardants, and industrial chemicals, and heavy metals like Ni, Cd, Cu, Cd, so that these chemicals can be up to a million times the levels in the surrounding water [30]. Microplastics can; therefore, be considered a vector that transports chemicals into organisms [33,34].

Microplastics have been detected in a number of environmental compartments around the world. For instance, scientists reported over 400,000 particles/km^2 in the Great Lakes, USA [35], while in a separate study, researchers reported 60 microplastic particles per 100 mL of sediment at Sydney Harbour [36]. In the USA they are mostly microfibers, whereas in Indonesia they are mostly microplastics from larger broken-down plastics. The majority of clothing fibers are synthetic, and research from the shoreline around the globe showed textile fibers are dominant [5,16,28]. The hypothesis was that fibers are escaping from washing machines, a phenomenon most likely to occur in developed countries. In fact, in recent research, it has been found that microfibers from synthetic textiles are one of a major sources of microplastics in the environment, irrespective of the country of origin [37].

The risk posed by microplastics varies with shape and size so that with a larger surface area, fibers will be more toxic than spherical beads [17,38]. Water reservoirs such as lakes and dams are particularly susceptible to microplastic pollution, hence there is considerable data on microplastic pollution characteristics in these ecosystems. A study on microplastics pollution in the backwaters of Xiangxi River reported microplastics concentrations in the range 0.55×10^5–342×10^5 items per square kilometer and 80–864 items per square meter in surface water and sediment, respectively [39]. Polystyrene (PS), polypropylene (PP), and polyethylene (PE) microplastics were reported in surface water, while PE, PP, and polyethylenterephtalate (PET) were predominant in sediment. Moreover, PE and nylon microplastics were also detected in the digestive system of 25.7% of fish. These results indicate the presence of microplastics in reservoir impacted tributaries and suggest water level controlled hydrodynamic conditions and nonpoint sources as key determinants for the accumulation and distribution of microplastics [40].

While the effects of microplastics as anthropogenic litter on the aquatic ecosystem have been documented [9,22], including the modeling of all plastics ever produced [6], many researchers on microplastics note the dearth of research data both in the oceanic environment and in freshwater sources [41–44]. Despite plastics being around for a long time, very little data exists on the abundance of both primary and secondary microplastics [45]. An increasing volume of reviews has appeared, ranging from exploring the whole spectrum of microplastics to discussing more specific laboratory methods of analysis and recommendations for quantification, the state of primary microplastics, and microbial degradation approaches [46]. Studies profiling the spatial distribution of plastic pellets on coastlines and others with implications to geographical specific ecosystems have been reported although this needs to be widened [18,47,48]. For example, the Mediterranean Sea, dubbed the most polluted sea in the world, has been intensively investigated [49,50]. This accumulation of data is critical in remediation strategies globally. It is also important to note that, despite several studies reporting on the quantification of microplastics, there is no standardized sampling, pretreatment, identification and quantification techniques of microplastics. Therefore, standardization and harmonization of the sampling and processing techniques is important for inter-study comparison of the data, monitoring pollution, and safeguarding the ecological integrity of aquatic ecosystems [51].

To abate the ecological impacts of microplastics, all stakeholders have to make concerted efforts. For instance, (1) governments can fund research that can lead to reduced risks of microplastics entering water bodies, (2) the general public can be encouraged to explore ways of managing plastic wastes through reuse, recycling and the recovery of resources locked away in these materials for sustainable community development, and (3) to minimize the plastics and microplastics load entering the aquatic environment, industry can adopt the cost-effective reduce-reuse-recycle (3Rs) circular economy [28,29,52,53]. Overall, these efforts will minimize the number of plastics that end up in the environment and impacting both aquatic and human health.

The specific aims were to (1) discuss the sources and routes through which microplastics enter the aquatic environment, (2) discuss the occurrence of microplastics in African aquatic systems, and (3) evaluate the pollution characteristics of microplastics in aquatic systems. In addition, the review evaluates and separates natural bio-accumulation of polybutylterephthalates (PBTs) in aquatic organisms from those leaching from microplastics, and offers recommendations for the remediation of microplastics pollution.

2. Methodology

A literature search in the Scopus database for “microplastics” in the “title, abstract or keywords” published from 1961 to 3 May 2021, resulted in a total of 5453 articles (S1). There were no differences in the annual publication output observed before 2011, and the numbers of published papers per year were less than 5 and 25 before 1970 and 2012, respectively (Figure 1). To screen the pertinent articles for this review, articles dealing with sources of microplastic, mechanisms of microplastic formation, fate and behavior of microplastics in environmental systems, health impacts of microplastics and their remediation options were selected based on their title, abstract and keywords. Moreover, to address up-to-date scientific research outputs with respect to microplastics, more emphasis was given to the latest publications in the period 2011–2021. The authors believe that this review is important in order to design and search for alternative best technologies for remediation of microplastics in the future.

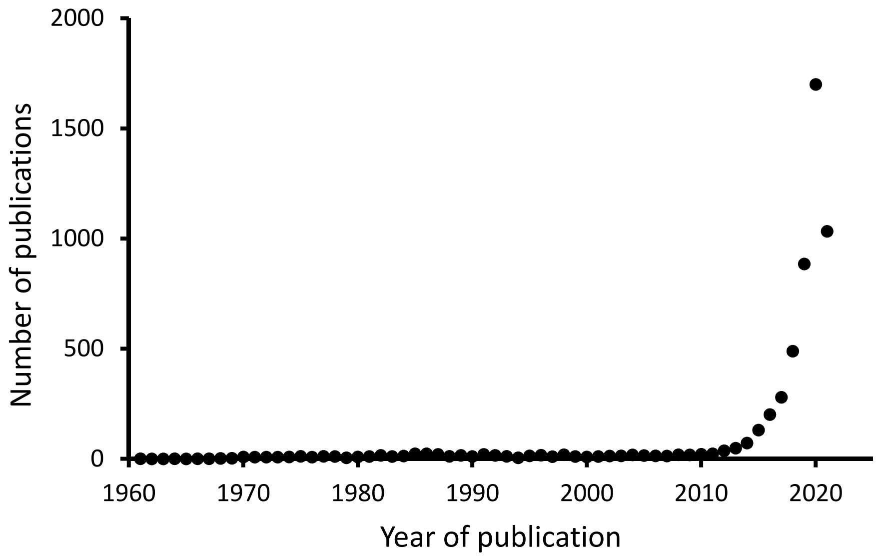

Figure 1. Number of papers published from 1961 to 3 May 2021 in Scopus database with microplastic in title, abstract or keywords.

3. Mechanisms of Microplastic Formation

Once formed, microplastics are transported via wastewater runoff and enter into municipality effluents, freshwater or marine system [5,54–56]. By virtue of their size, these particles are not retained by the conventional water filtration systems, and find their way into water bodies, thus posing a potential threat to aquatic and human life. Secondary microplastics are produced from larger pieces of plastics breaking down into smaller fragments due to environmental stress, cracking, and degradation associated with weather conditions and biological and UV attacks [16,19]. The plastics are also broken down by the abrasive effect of waves against the coastal sand and rocks (Figure 2).

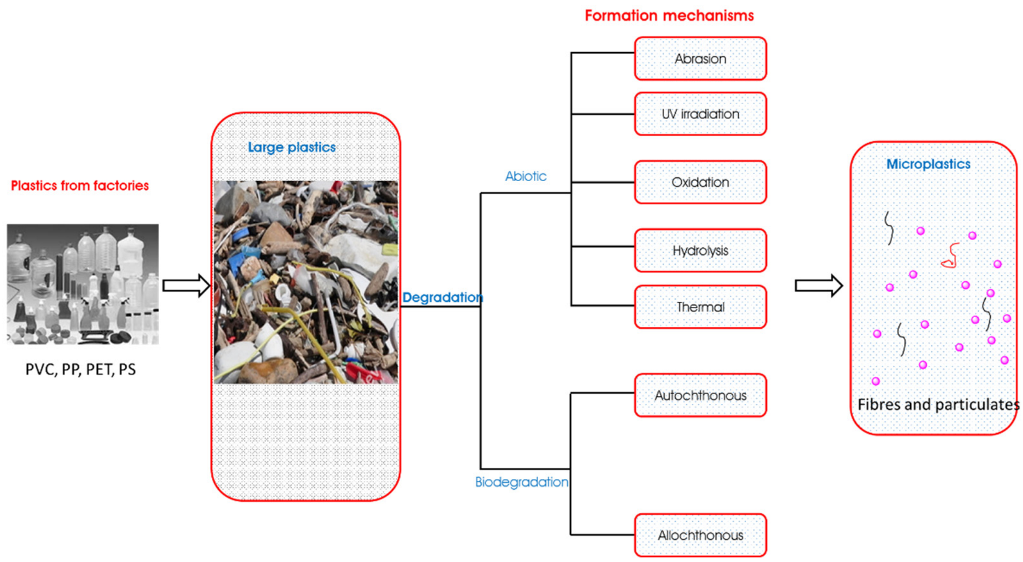

Figure 2. Mechanisms of degradation of plastics into microplastics.

The process of plastics degradation by physical and chemical influences into microplastics is known as abiotic degradation. The major factors contributing to abiotic degradation of plastics are UV-irradiation, oxidation, thermal impacts, hydrolysis, and abrasion due to wave action in the seas and oceans [57].

Most commonly used plastics are non-biodegradable; consequently, they accumulate in the environment [6]. Biodegradation of plastics usually occurs in both the aquatic and terrestrial environments. In the aquatic environment, particularly at the benthic level, biodegradation rates are insignificant. This is largely because of the decreased population of microbes in these environments. In shallow waters; however, there are a variety of microbial communities that are crucial in the biodegradation process [57]. Generally, the degradation of plastics through biotic means is a complex process and requires a combination of various types of microorganisms for complete degradation into microplastics.

4. Microplastics in Environmental Compartments

Despite several studies on microplastics, their fate in the environment is poorly understood. Numerous studies have shown microplastics are prone to degradation, and are easily dispersed in the indoor and outdoor environment [3,58–61]. Due to the hydrophobic nature of microplastic surfaces, they can significantly adsorb toxic organic contaminants and are considered as vectors for most persistent organic pollutants (POPs) listed under the Stockholm Convention [56]. However, plastics have a higher likelihood of behaving as a passive sampler rather than a vector for POPs [62]. In addition, microplastics can act as bacterial careers. For instance, studies reported potentially pathogenic Vibrio parahaemolyticus on microplastics from North/Baltic Sea [63]. Thus, future studies should not only put emphasis on toxic chemical transportation of microplastics to living organisms, but also on the pathogens they potentially transport. Overall, the physical, chemical properties and environmental conditions in which microplastics are available mainly determine their transport and fate. Therefore, detailed investigation of these factors deserve further research.

The smaller size of microplastics coupled with their low density makes them to suspend in the air and easily be inhaled and create potential health problems [64]. Among the various microplastics, fibers are an abundant significant source of microplastics in the marine and atmospheric environment, and when ingested, could release different types of pollutants in living organisms [55,65]. However, a thermodynamic method for evaluating the environmental exposure of chemicals adsorbed to microplastics showed a low significance of microplastics as a vector for persistent, bioaccumulative and toxins, relative to other exposure pathways [66]. Nonetheless, as pointed out by the researchers, this study was limited by lack of data on kinetics, chemical interactions (desorption and adsorption), the influence of microbial biofouling, assessment of the fate of the microplastics in a microorganism to improve understanding.

To facilitate the management of microplastics and reduce their environmental impacts, the sources, fate, and environmental behavior of microplastics have to be understood [67]. The following sections provide a brief review of mechanisms of microplastic formation, their behavior, and fate in different environmental compartments.

4.1. Aquatic Environment

The position of microplastics in aquatic systems is influenced by various dynamics including fouling and their density, and determines their impacts on marine organisms. After fragmentation, lower density microplastics float on the water surface, while higher density ones sink to accumulate in the sediment [68,69]. Thereafter, there is an interchanging of the microplastics between biota, water, and sediment through bioturbation, ingestion, and excretion (Figure 3). In fact, the freshwater input with the accompanying turbulence can result in the mixing or disturbance of microplastics in the sea or ocean, causing a redistribution of the microplastics. A recent modelling study on the transportation of microplastics confirmed that river hydrodynamics greatly influence microplastics distribution in rivers and their introduction into marine systems [70].

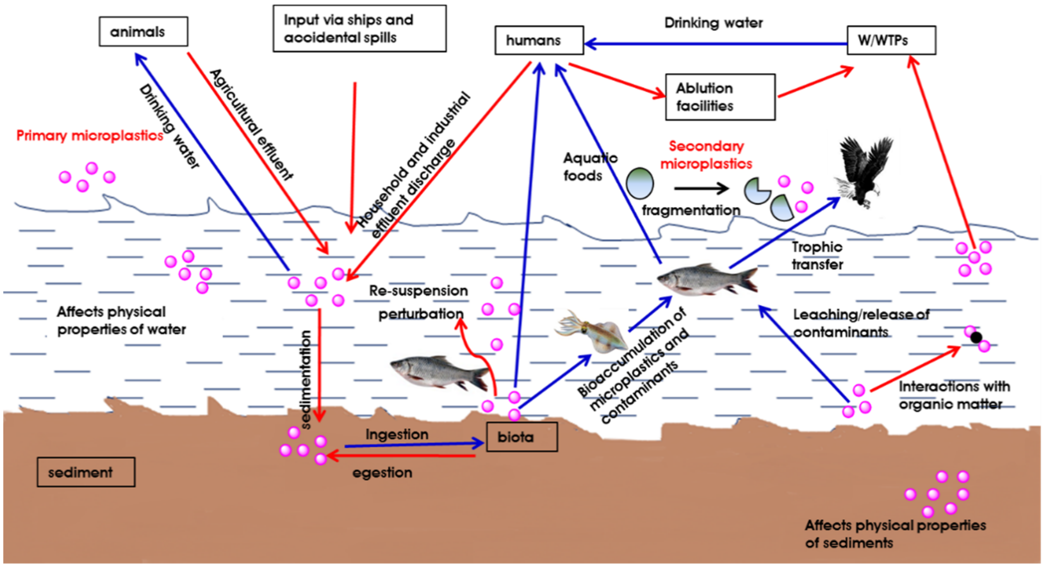

Figure 3. An illustration of the occurrence and fate of microplastics in aquatic systems.

Several studies have highlighted the presence of microplastics in aquatic biota, but the impact of ingestion by various organisms is not adequately researched. Microplastics in the aquatic environments can be ingested by invertebrates, fishes, birds, marine mammals. Once ingested, they transfer toxic chemicals which are either adsorbed onto the microplastics during emission and transportation or additive toxic chemicals added during the manufacturing process [71]. Large amounts of microplastics are expected in the aquatic biota; however, there is no experimental evidence that clearly shows whether microplastics transfer greater concentrations of pollutants to tissues than sediments or whether microplastics are capable of transferring high concentrations of pollutants to impair functions of organisms [72]. Therefore, this area requires detailed future investigation. Furthermore, taking into consideration the high amount of global seafood consumption, for example over 125×10^6 tons in 2009 [22], the contamination of human food by microplastics should get more research attention.

For a while, microplastic pollution has been considered a marine problem, but recent work has reported microplastics in freshwater systems [73]. The work by several researchers provides an indication on the prevalence of microplastics in freshwater in Africa, Asia, Europe, and North America [35,73–78]. Evidence from these studies suggests that freshwater and marine systems have similarities in the forces that facilitate the transport of microplastics such as surface currents, and the potential effects like damage to the physiology of organisms, as well as transfer of toxins. However, differences between freshwater and marine environments include the closeness of microplastics to their original sources in freshwater. This has led to differences in the types of microplastics in freshwater bodies like rivers, which show a predictable trend with regard to shape, size, and relative abundance [79].

Although microplastics have been reported in freshwater [73,80,81], data on the presence and distribution of microplastics in the freshwater environments is sparsely available. Consequently, there is still a lack of detailed studies on the relative load in the two environmental compartments [82]. Considering that humans are highly dependent on freshwater sources for drinking and other uses, limited knowledge on the transfer of microplastics from freshwater to terrestrial environments and their potential impact on human health is cause for concern. In order to develop suitable policy and management instruments to mitigate the impact of microplastics on freshwaters, there is a need to fund research, and promote education and awareness to the wider population, especially in developing countries.

4.2. Soil and Sediment

While microplastic contamination of marine environments is widely acknowledged [7,83,84], studies on the availability and negative effects of microplastics in the soil are scarce. Microplastics can potentially impact soil ecosystems, plants, and animals due to toxic chemicals incorporated during the manufacturing process [7]. A recent review that assessed the contamination of soil by microplastics deemed that the contamination reached high concentrations identical to those of toxic metals [85]. As to the sources of microplastic to the soil, sewage sludge is a key source of microplastics into the soil. Despite the presence of toxic chemicals in microplastics as well as their high adsorption capacity for harmful pollutants from the surrounding environments, sewage sludge is commonly used as a fertilizer [77,86,87]. For instance, in Europe and North America, 50% of sewage sludge processed from municipal wastewater treatment facilities is used in agricultural farmlands [7]. This suggests that agricultural lands receiving sewage sludge are potential reservoirs of microplastics. A recent study on the transport of surface deposited microplastics into the soil has shown that soil microarthropods are responsible for the accumulation and distribution of microplastics in the soil food web [84]. However, detailed studies in this area are lacking. Therefore, immediate research and detailed investigation is required to ameliorate the effects of microplastics on the terrestrial ecosystem.

Microplastics in sediments have been widely reported globally. A study on the coastline of East Frisian Island reported high levels of microplastics in fine-grained sediments [88]. In most cases, small plastic fragments, and seawater containing microplastic fibers enter the coastal sediments and increase the concentration of microplastics in sediment [89–91]. In other studies, high levels of microplastics were reported in the sediments sampled from Edgbaston Pool in the UK [92], and Changjiang Estuary in China [91]. A concentration of 20–30% (w/w) microplastics was reported in sediment samples collected from Edgbaston Pool in the UK, while the mean concentration of 121 ± 9 per kg of dry weight sediments were reported in Changjiang Estuary, China. Similarly, high concentrations of microplastics were detected in the Mediterranean Sea north-western Adriatic beach sediments [93], and in beach sediments along the South-eastern coastline of South Africa [94]. Overall, research on identifying and quantifying microplastics in sediments indicates that sediments are one of the main reservoirs of microplastics. However, the reason for microplastics sinking in sediments due to physical or biological processes requires detailed study.

5. Interaction of Microplastics with Pollutants

Microplastics can scavenge most organic pollutants and toxic metals in the environment. Consequently, they are carriers of toxic substances like pesticides, polychlorinated biphenyls, and polycyclic aromatic hydrocarbons [3]. Particularly, the organic pollutants are well known to be resistant towards chemical, biological or photocatalytic degradation. Thus, the ingestion of microplastics onto which these toxicants adhere exposes organisms and humans to hazardous chemicals [57]. The accumulation of toxic metals such as Cd, Ni, Pb, and Zn has been reported [95,96]. Furthermore, the study investigated on the influence of microplastics on toxic metals adsorption in stormwater demonstrated that microplastics are vector for toxic metal transportation from urban environment to the water resources [97]. The ease of scavenging of toxic chemicals by microplastics is largely owing to their small size and hydrophobic nature [18,56].

In addition, microplastics may also contain toxic chemicals which are embedded during manufacture for the purpose of protecting plastic from fire risk (e.g., polybrominated diphenyl ethers, phthalates, nonylphenols, bisphenol A, polybromobiphenyls, polychlorobiphenyls), antioxidants to protect microbial growth (e.g., triclosan), and UV stabilizers to inhibit degradation on exposure to sunlight [72,98–100]. When the additives are not chemically bonded to the polymer molecules, they can be easily released from the plastics and subsequently transferred to water, sediment, and living organisms [3,82,101]. Ingestion of microplastics by marine microorganisms, animals and humans may result in physical and toxicological effects [1,91]. The physico-chemical characteristics of microplastics such as size, density, and chemical composition are key attributes for their bioavailability to the organisms [69,102]. When these pollutant-laden microplastics are ingested by marine organisms, they do not only negatively affect the proper eco-physiological functions of microorganism but also have a severe impact on the aquatic food web [3,22,72,96].

6. Environmental and Health Risk Associated with Microplastics

Recently, the potential environmental risks and impacts of microplastics have received considerable research attention [103–107], with calls to declare microplastics hazardous and constituting a planetary boundary threat among other such threats as climate change, ozone depletion, and ocean acidification. The environmental and public health risks of microplastics in aquatic systems can be broadly grouped into direct and indirect [108]. Direct impacts are expressly associated with microplastics, while indirect impacts are associated with the release of potentially toxic micropollutants and the transportation of pathogens. Documented impacts include intake by aquatic organisms such as fish, and prolonged release of potentially toxic contaminants [25,109]. Once in aquatic systems, these microplastics and associated contaminants can be taken up and bioaccumulate in aquatic organisms and sediment [69,108,109]. Major sinks in aquatic systems remain unknown. Limited studies have reported the partitioning of microplastics in solid and liquid phases of aquatic systems such as various sediment size fractions, aquatic plants, fish and other organisms and the dissolved fraction. Considering that aquatic systems are a source of various human foods including fish, water, and salt, potential risks exist for microplastics to enter the human food chain [109]. Once in aquatic systems, microplastics may act as a source of potentially toxic contaminants such as PBTs. However, few studies have so far been conducted in developing countries [94,108,110–114], and here the risk could be high due to lack of legislation and poor enforcement. Moreover, water treatment methods used for drinking water and wastewaters have limited capacity to remove microplastics because technologies such as membrane filtration are not available in most developing countries because of cost limitations.

A number of reviews exist on the potential environmental risks of microplastics in aquatic systems and future research priorities [35,56,68,115,116]. The environmental health risks of microplastics are dominated by studies focusing on effects on wildlife and aquatic ecosystems, while those on human health are relatively limited (Table 1).

Table 1. Summary environmental, ecological and potential public health risks/impacts of microplastics in aquatic systems.

Risk/Impact Example	**Effect**	**Reference**
(1) Vector of anthropogenic organic contaminants:		
Polybrominated diphenyl ethers (PBDE) congeners	Microplastics contaminated with PBDE congeners mistaken for food by marine Amphipod (*Allorchestes compressa*) and assimilated	[117]
Triclazan (anti- microbial additive to plastics)	Triclazan reported in a marine sediment lug worm. Triclazan causes reduction in immune function and survival, reduction in ability to feed and process sediments	[72]
Phthalates	Phthalates are capable of inducing endocrine disruption and dysfunctional reproductive system observed in a laboratory study on fish	[16]
Inorganic contaminants e.g., Zn	Microplastics acted as a vector for Zn, by increasing its bioavailability to earthworms, there was no evidence of Zn accumulation, mortality or weight change in earthworms.	[118]
(2) Aquatic ecosystems/food webs:		
Ingestion of microplastics by aquatic organisms	Shore crab (*Carcinus maenas*) take up microplastics via inspiration across the gills and ingestion of pre-exposed food (e.g., mussel *Mytilus edulis*).	[104]

Table 1. *Cont.*

Risk/Impact Example	Effect	Reference
	Zooplanktivores confused paint and styrofoam microparticles natural prey.	[17]
	Microplastic ingestion was observed in three demersal fish species from the Spanish coasts, the abundance of microplastics (33.3%) occurring stomachs of red mullets followed by dogfish (20.8%)	[119]
Mortality, growth and survival of organisms	Exposure sea urchin (*Tripneustes gratilla*) to polyethylene microsphere concentrations exceeding those in marine environment a small non-dose dependent effect on larval growth, but there was no significant effect on survival because the microplastics were egested within hours of ingestion.	[120]
Acute physiological effects on osmoregulatory and respiratory functions	Acute aqueous exposure of shore crab *Carcinus maenas* to polystyrene microplastics (diameter: 8 μm) had significant but transient effects on branchial function and ion exchange. Significant dose-dependent effect on oxygen consumption was observed after 1 h of exposure, returning to normal levels after 16 h, while a significant decrease in hemolymph sodium ions and an increase in calcium ions occurred after 24 h post-exposure.	[106]
Reproductive effects	Virgin and beach-stranded plastic pellets microplastics increased anomalous embryonic development of sea urchin (*Lytechinus variegatus*) by 58.1% and 66.5%, respectively, but toxicity of stranded pellets was lower than virgin pellets. Plastic pellets act as a vector of pollutants, especially for plastic additives found on virgin particles.	[121]
Chronic alterations in digestive system of aquatic organisms	Microplastics caused histological alterations in distal intestinal of European sea bass *Dicentrarchus labrax* after 60 and 90 days of exposure polyvinylchloride (PVC) microplastics.	[122]
Earthworm mortality and growth	Polyethylene microplastics caused significantly higher mortality of earthworm *Lumbricus terrestris* after 60 days at 28%, 45%, and 60% of microplastics in the litter than at 7% w/w and in the control (0%). Growth rate was also significantly reduced at 28%, 45%, and 60% w/w microplastics, compared to the 7% and control treatments. This has implications on the fate and risk of microplastic once dredged from aquatic systems and disposed of in terrestrial ecosystems.	[123]
(3) Human health risks:		
Consumption of microplastic contaminated aquatic foods	Microplastic accumulation in human body, localized particle toxicity, and chemical and microbial contaminants arising from microplastics ingested or inhaled.	Human consumption of bivalves, [56] Consumption of commercial salt, [31]
Vector of pathogenic organism and disease vectors	Transmission of pathogens, fecal indicator organisms and harmful algal bloom species (HABs) across beach and bathing environments and potentially promote the spread of infectious diseases	[124]

6.1. Aquatic and Terrestrial Risk/Impacts

Numerous studies have investigated the ecological effects of microplastics covering various species life cycles, growth stages and species [119,123]. These studies focused on ingestion of microplastics by aquatic organisms [103–105], microplastics as vectors of organic and inorganic contaminants [34,125,126], and impacts on physiology, digestive system, reproduction, growth, and survival [106,121]. Several aquatic organisms including fish, crustaceans, and zooplanktivores confuse microplastics and ingest them as food [58,104,127]. Shore crab (*Carcinus maenas*) and zooplanktivores absorb microplastics via the gills and through the consumption of pre-exposed food (e.g., mussel *Mytilus edulis*) [17,104]. In addition, three fish species from the Spanish coasts were reported to ingest microplastics, with the abundance of microplastics occurring in stomachs of red mullets (33.3%) followed by dogfish (20.8%) [119].

The ingested microplastics may have adverse physiological effects on aquatic organisms. For example, microplastics caused histological alterations in the distal intestinal of European sea bass (*Dicentrarchus labrax*) after 60 and 90 days of exposure to PVC microplastics [106]. Acute aqueous exposure of the shore crab (*Carcinus maenas*) to PS microplastics had substantial temporary effects on gill function and ion exchange. Significant dose-dependent effects on oxygen consumption were observed after exposure for an hour, normalizing after 16 h, while a significant reduction in hemolymph Na^+ ions and a rise in Ca^{2+} ions occurred subsequent to a 24 h exposure.

Besides ingestion and the physiological impacts of microplastics, other studies investigated the toxicity of microplastics to various growth phases of biota. Using virgin and beach-stranded plastic particles to investigate the toxicity of microplastics on sea urchin (*Lytechinus variegatus*) embryo development, a study showed that plastic pellets are vectors for pollutants, and the toxicity of leached chemicals is dependent on the route of exposure and the environmental compartment in which plastic particles accumulate [121]. In another study, florescent microscopy confirmed size and dose dependent toxicity of microplastics on goldfish [128]. The study found higher concentrations of small-sized microplastics in the intestine and liver, while larger particles with higher concentration in the gills of goldfish. However, a pervious study that compared different tissues reported the highest concentrations of accumulated small sized microplastics were found in the order of gill > intestine > liver [129]. From these contradicting results, it is possible to see that there is a need for further re-search, taking into consideration the species type, shapes of microplastics, nature of the environment, and exposure times. Furthermore, there is a need to develop a standardized protocol that allows comparison of research data across different studies. Overall, despite being ubiquitous in the environment, the acute and health impacts of microplastics are not well known [130]. However, it has been confirmed that the accumulation of microplastics in lungs can cause inflammatory and oxidative stress [64].

Another study investigated the influence of PE microplastics in sediment on polychlorinated biphenyls (PCB) uptake by a marine lugworm (*Arenicola marina*) by measuring uptake from natural exposure routes [70]. Based on the concentrations of PCBs in sediment, biota lipids, and pore water, metrics such as bioaccumulation factor (BAF), biota plastic accumulation factor (BPAF), biota sediment accumulation factor (BSAF), and lipid-normalized bioaccumulation (Clip) were calculated. The addition of PE produced small effects, suggesting slight fluctuations in bioaccumulation, but the decrease depended on the metric of bioaccumulation, which followed the order: Clip > BSAF > BPAF > BAF. Using a biodynamic model, the researchers concluded that PE microplastics did not behave as a quantifiable vector for PCBs. Another study reported that the rates of desorption of dichlorodiphenyltrichloroethane, di-2-ethylhexyl phthalate perfluorooctanoic acid, and phenanthrene on PE and PVC was 30 times more rapid under simulated gut conditions than in seawater, with an additional increase under conditions mimicking warm-blooded organisms [126]. This indicates the need to perform such studies under physiologically realistic conditions. In another study, microplastics acted as a vector for Zn by increasing its bioavailability to earthworms [118]. However, there was no Zn accumulation, mortality or weight change in the earthworms. In other studies, PE microplastics increased the mortality of earthworm *Lumbricus terrestris* (*Oligochaeta*, *Lumbricidae*) after 60 days at 28%, 45%, and 60% load in the litter than at 7%, and in the control [123]. The growth rate was also decreased at 28%, 45%, and 60% load, relative to the 7% and control treatments. These concentration-transport and size selection mechanisms could possibly influence the fate and risk of microplastics in soil environments.

Most studies on the impacts of microplastics on aquatic organisms largely focus on virgin and spherical polymer microplastics, while the effects of biofilm formation on behavior and fate of microplastics have received limited attention. Moreover, the ecological complications of biofilms on the behavior, fate, trophic transfer, and risks of microplastics are still poorly understood. The few available studies (e.g., [131]) suggest that biofilm-plastic interactions affect the fate and impacts of microplastics by altering the physicochemical characteristics of the particles. However, more studies are required to explore these interactions and enhance the environmental relevance of laboratory experiments by simulating real-life conditions and microbial controls, which are key drivers of biogeochemical processes.

Although most studies seem to suggest adverse environmental impacts on aquatic organisms, a few exceptions exist: (1) One study reported that microplastics had negligible effects on marine larval growth and survival [120], (2) other studies even show that microplastics provide distinct microhabitats for novel microbial assemblages capable of breaking down plastics [132,133], and (3) another study showed that high concentrations of microplastics created a micro-habitat that promoted reproduction of aquatic organisms [134]. For example, exposing sea urchin (*Tripneustes gratilla*) to PE microsphere concentrations greater than those in the marine environments showed no significant effect on survival because the microplastics were egested within hours of ingestion [120]. The study further showed that environmentally relevant concentrations had little effect, and concluded that the levels of microplastics in the oceans studied did not pose a significant risk to T. gratilla and other marine organisms. However, they recommended further research with an increased scope of aquatic species, trophic levels, and polymers. Another study reported that microplastics originating from wastewater treatment effluent constituted an abundant and distinct microbial micro-habitat in a highly urbanized river in Chicago, Illinois, USA [132]. Sequencing techniques revealed that bacterial clusters in microplastic habitats were more similar, but had significantly diverse taxonomic make-up including plastic degrading organisms and pathogens relative to those in the water column and suspended organic matter. The study concluded that microplastic habitats potentially acted as vectors for downstream transportation of bacterial assemblages, which could assist in the degradation of plastics in the global microplastic cycle. A few other studies indicate limited importance of microplastics for bioaccumulation under environmentally realistic conditions [123,135], while others report significant ecological effects [126]. These seemingly contradictory results among various studies demonstrate the need for caution when extrapolating results from laboratory conditions to actual environmental conditions, and from one species to another.

The ecological effects of microplastics appear to depend on several factors, such as concentration, type, and age of microplastics, species and developmental stage of the bioassay species used, and the potential interactions of microplastics with organisms (e.g., biofilm formation and media (pore water, sediments)). These findings emphasize the need to conduct studies under environmentally and physiologically realistic conditions and consider various media and transfer pathways in assessing the ecological effects of microplastic exposure on aquatic ecotoxicology.

6.2. Human Health Risks

Aquatic systems provide recreational sites, water for household uses, and are sources of various human foods including fish, crustaceans, and salt. Microplastics have been detected in edible aquatic organisms such as fish, crustaceans, and molluscs [22,119,136,137], and commercial salt used for human consumption [31]. Therefore, once in aquatic systems, microplastics and associated contaminants and microbes can be transferred to humans via direct dermal contact and ingestion of contaminated water and aquatic foods. Microplastics may also act as sources and vectors of potentially toxic anthropogenic organic contaminants introduced either intentionally (e.g., during the production of plastics) or unintentionally (through surface adsorption through microplastic life cycle). There is increasing evidence that contaminants may bioaccumulate in the trophic system and be transferred to humans through the consumption of contaminated aquatic foods [21]. For example, microplastics were found in the soft tissues of bivalves (*Mytilus edulis* and *Crassostrea gigas*), and at the time of consumption, *M. edulis* contained 0.36 ± 0.07 microplastics per gram, while 0.47 ± 0.16 particles per gram were observed for *C. gigas* [22]. The authors estimated the annual dietary exposure of European shellfish to be up to 11,000 microplastics, thereby posing a potential threat to food safety.

A detailed treatment of specific human risks posed by microplastics in the environment is outside the scope of this review. Nevertheless, humans are exposed to microplastics through a number of routes such as drinking water and food. For instance, commercial salt extracted from oceans has been reported to contain microplastics. For example, microplastic-like particles extracted from 17 salt brands from eight countries showed that 16 of the salts contained one to 10 microplastics per kg of salt, while the remainder had none [31]. The extracted particles comprised of 41.6% plastic polymers, 23.6% pigments, and 5.5% amorphous carbon, while 29.1% were unidentified material. Based on the microplastic concentrations and typical human daily salt consumption, the estimated maximum human annual intake was 37 particles per individual, a concentration with insignificant health effects.

Microplastics in aquatic systems can also behave as vectors that facilitate the dissemination and persistence of pathogenic organisms, fecal coliforms, and algal blooms [138]. A review of epidemiological studies investigating the relationship between the quality of bathing water and adverse effects on human health (e.g., gastrointestinal and respiratory disorders, and eye, nose and throat infections) concluded that microplastics provided possible microhabitats for harmful organisms [124]. This could, in turn, promote the proliferation of these organisms in marine ecosystems and the spread of infectious diseases. Potential acute and chronic human health risks may also occur through microplastic accumulation in the human body [56]. For instance, the accumulation of microplastics may cause localized toxicity by inducing an immune response, while the leaching of additives, residual monomers, and adsorbed pollutants can result in chemical toxicity. Dose-dependent chronic exposure to microplastics could be concerning owing to the accumulative effect given the persistence of microplastics.

Overall, based on the few available studies [31,56,119], a robust evidence-base demonstrating acute and chronic effects of microplastics is still lacking. This is partly because the accurate determination of the potential human health risks posed by microplastics in foodstuffs is still problematic due to the challenges associated with quantifying microplastic toxicity to humans. However, although documented human risks or impacts traced to microplastics are still lacking, the human health risks could be high in cases where such microplastics are contaminated with highly toxic organic contaminants. To better understand the human epidemiology and ecotoxicology of microplastics, there is a need to further research on developing extraction protocols to isolate small anthropogenic particles and investigate the human ecotoxicology of microplastics laden with toxic contaminants. Such information is critical to understanding the mechanisms of toxicity and, hence, the development of mitigation measures to safeguard human health.

6.3. Microplastics in African Aquatic Systems

Most literature on microplastics is from the developed world (e.g., [60,62,77,81,125,127,136]), with very little reported in developing countries. The literature on remediation in these developing countries is even sparsely available. However, microplastics have been detected in sediments, sea birds, and marine organisms on the coasts and estuaries of South Africa [94,111,113,114], and Tunisia [108] (Table 2). Research on microplastics in inland freshwater sources in Africa has only just begun, with reports on the detection of microplastics in Nile tilapia and Nile perch from Lake Victoria [110,112], and in household salt [31]. A recent review provided an in-depth data synthesize on the abundance, distribution, and fate of microplastics in African aquatic systems [139]. The study reported that, while a number of studies investigated the occurrence of microplastics in marine systems, there was very little data on other environmental compartments, namely the terrestrial environment, the atmosphere, and freshwater systems. Sources of the microplastics are thought to include fishing, tourism, and urban waste [73]. In addition, with the COVID-19 pandemic and its accompanying use of plastic-based protective and hospital equipment, the concentration of microplastics in the environment is likely to rise in the near future.

Table 2. Microplastics in African aquatic systems.

Country	Location	Sample Types	Occurrence	Abundance	Particle Size (nm)
South Africa [140,141]	Estuaries of KwaZulu-Natal River system, South Africa	Fish	Natural microfibres (70.4%), polyethersulphone (10.4%)	5.54 ± 3.26 p/100 m^2 (winter)	0.02–0.5
			Nylon (5.2%) and PVC (3.0%)	2.96 ± 2.94 p/100 m^2 (summer)	
		Water	Fibers: blue (92%)	2.3 ± 7.2 p/L (wet season), 1.4 ± 2.6 p/L (dry season)	
South Africa [142]	Braamfontein Spruit	Stream sediment		166.8 p/kg (dw)	0.053–4
	Johannesburg				
Ghana [143]	Sakumo II	Water		0.09 p/mL	0.1–5
Ghana [144]	Eastern Central Atlantic Ocean	Marine sediment		3.2 ± 2.7 dw	
Nigeria [145]	South Eastern Coast	Surface water		410–1556 p/L	
Nigeria [146]	Yenogoa	Lake sediment		1004–8329 p/m^3 (dry season)	0.02–0.5
				201–8369 p/m^3 (wet season)	
Kenya [147]	Centra Kenya	Surface water		110 p/m^3	0.25–2.4
Kenya [148]	Naivasha	Lake surface water		0.407 ± 0.135 p/m^2	1–5
Egypt [149]	Eastern Harbour	Seawater		83–174 p/100 g (dw)	0.5–5
Ethiopia [150]	Lake Ziway	Freshwater		6.3–115.9 p/kg (dw)	0.5–5
Tunisia [151]	Southern Mediterranean	Marine sediment		129–606 p/kg (dw)	0.0001–1
Tunisia [152]	Gulf of Annaba	Marine sediment		182.66 ± 27.32–649.03 ± 184.02 dw	0.81–2.16

p stands for particles, dw is dry weight, and ww is wet weight.

Considering the vast size of the freshwater bodies in Africa, and the large populations they support, there is considerable potential for microplastics pollution in these waters [73]. Given the lack and/or poor enforcement of environmental legislation in developing countries, and the resultant poor solid waste and wastewater management practices, the prevalence of microplastics in aquatic environments could be greater than initially thought. In these developing countries, where a considerable proportion of the population relies on untreated groundwater and rivers for drinking purposes, the human health risk could be potentially high. Moreover, conventional water treatment facilities, which are usually overloaded and ineffective, may be inadequate for the removal of microplastics because advanced water treatment technologies (e.g., membrane filtration) are unavailable due to cost constraints. Therefore, research on microplastics in aquatic systems and aquatic foods and their potential human health risks in developing countries warrants further research. However, such research efforts could be hampered by a lack of analytical equipment and expertise to conduct such studies.

7. Remediation Strategies

A number of methods, including the conventional wastewater treatment process, can be used to reduce microplastics pollution, especially the aquatic environment. A more detailed description of these and other methods is provided in a recent review [153]. A credible remediation strategy should recognize a number of issues with respect to the existence of the microplastics problem, chief among which is the entrance and persistence of plastics in the environment. The problem of microplastics is thus a derivative of plastics and the linear approach to the production, consumption, and disposal of plastics in the economic lifecycle [154]. A recent review on plastics suggested that the global production capacity of biodegradable plastics is only 4 Mt [6]. This presents an opportunity to promote the production of these materials which could be environmentally benign. Examples of commercially available biodegradable plastics that can potentially replace traditional plastics for a range of applications include polylactide, polyhydroxyalkanoates [19].

Meanwhile, the most widely practiced approach in managing plastics is recycling. Global recycling rates have gradually risen to account for 24% of non-fiber plastic waste produced in 2014. In that year, the most recycling was in Europe (30%) and China (25%), while in the United States it was 9%, a value comparable to the rest of the world [6]. To date, textiles are not commonly recycled but are incinerated or co-disposed with other solid waste. Around 53% of the plastic waste is used for energy and 46% for recycling, and about 1% ends up on dumpsites [155]. Overall, while recycling can prolong the life of plastics before they are finally disposed of into the environment, the handling that is associated with recycling processes can potentially generate microplastics.

One of the major drawbacks of plastic is their poor biodegradability. Bioremediation appears to be an attractive strategy for mitigating the spread and effects of microplastics and this has been demonstrated by a pilot-scale Anaerobic Membrane Bioreactor (AnMBR), showing that it is possible to release only small anthropogenic litter (SAL) per liter, with a removal rate of 99.1%, by combining tertiary treatment (membrane filtration) and the AnMBR [43]. It is likely that the SAL would include microplastics. Because they are located in the course of most rivers where water is drawn for industrial consumption, wastewater treatment plants (WWTPs) are key facilities that can remove and treat most aquatic debris, and the sludge generated from WWTPs is a major source of microplastics [156]. Reports show that 95–99% SAL can be retained in WWTPs although some of the microplastics still find their way into aquatic bodies. In a separate study, a bacterium, *Ideonella sakaiensis* 201-F6, which can digest PET as a source of energy while producing terephthalic acid and ethylene glycol, which are less harmful, was isolated [157]. It has also been demonstrated that two strains of bacterium *Enterobacter asburiae* YT1 and Bacillus sp. YP1 extracted from Indian meal moths is capable of damaging the PE surface, notwithstanding this thermoplastic has been regarded as non-biodegradable for a long time [158]. Other researchers have reported fast hydrolysis of PEs to ethylene glycol [159], and other findings have reported varying degrees of degradation of plastics on a laboratory scale [160]. A number of reviews have dealt expressly with the biodegradation of plastics [4,46,161], a stark realization for the need for urgent application on plastics in general as this technology can act as platforms for recycling of plastics.

Given the increasing trend in plastics production driven by the economic benefits, one counter-strategy would be to impose a moratorium on the production of plastics in efforts similar to limiting greenhouse gases [2]. As the perceived benefits of plastics seem to justify the continued growth of plastics production, it seems inconceivable that unless drastic measures are taken, SAL will continue accumulating in both the marine and freshwater ecosystems [48]. Several countries, including Bangladesh and a few in Africa, have adopted measures to ban single-use plastics through outright prohibitions, impositions of taxes on the sale or use of plastics [3,9]. It has been estimated that of the 8.8 metric ton that end up in the oceans per year [3], the top 20 countries out of a total of 192 countries studied contributed about 83% of the plastic waste in 2010, and, by extrapolation, by 2050 there could be more plastics and plastic fragments in the aquatic environment than the population of fish [45].

This bleak outlook requires urgent action in order to abate the ecological risk of microplastics. For example, through the Microbeads-Free Waters Act of 2015, the USA banned plastics microbeads in personal care products [162]. In Zimbabwe, the Environmental Management Agency (EMA) banned the production of expanded polystyrene because it causes the blockage of storm drains and is potentially a health hazard. Following extensive research, the manufacturing of thin-film plastics for carrier bags was banned in South Africa [163]. Although this raft of legislation can lead to temporary losses in jobs and revenues, they remain positive efforts to stop any further pollution into water bodies and such efforts need to be complemented globally. However, while plastic recycling protocols are well established in developed countries, in developing countries they usually lack legal support and thus their execution and enforcement are on an ad hoc basis [73].

Natural biodegradable products such as ground almonds, pumice, and oatmeal have traditionally been used as scrubbers in facial cosmetic products, and as such, a complete reversion to these products remains a viable alternative [18]. A UK House of Commons report notes that most private companies have made an undertaking to stop the use of microbeads by 2020, a commendable step that needs to be incentivized [164]. The occurrence of microplastics in foodstuffs such as commercial sea salt has potential direct human health impacts and requires a regulation. Such strategies can also be extended to any other marine products which are susceptible to the accumulation of microplastics.

The Waste Remediation (WR) tool has been suggested as one way of managing marine waste as part of Ecosystem Service (ES) framework in which the normal functioning of any environment can be used to convert waste into benign products within the ecosystem itself [165]. This warrants further investigation insofar as such ES frameworks have been tested and evaluated in studies akin to microplastics remediation [166].

Indeed there is a realization that the solution to microplastics pollution lies not only with re-engineering the production process, but also with the consumption of plastics along the value chain [167]. Importantly, awareness of microplastics pollution should perhaps match the levels climate change issues have been mainstreamed. Because of the low awareness to the extent of a low index of 25% of participants of a recently held survey [168], there is need to integrate all stakeholders to create awareness, which is key to mitigation and containment efforts [169,170]. Collaboration between various stakeholders can help create platforms for containment and mitigation. For instance, in California such initiatives have brought together the strengths of legislation, science, and regulators to define protocols for detecting microplastics in drinking water [171].

8. Recommendations

The area of marine and freshwater pollution by microplastics deserves much research attention, and this needs scientific data to inform environmental movements and policy-makers. Recent studies with extrapolations thereof have helped to mainstream the problems associated with plastics and microplastics [6,45]. Compared to microplastics, other topical issues, such as climate change and global warming, have received significant attention over the years as a result of state of the art studies which have generated data for policymakers [172]. Similarly, with adequate scientific evidence to demonstrate the ecological impact of microplastics, similar approaches can be taken to ameliorate the ecological impacts associated with microplastics. Each country needs to undertake research and practices to quantify its plastic footprint and generate a plastic waste index that takes into account all the plastic that is manufactured, imported, exported, incinerated, and recycled. This index will rank countries and help recommend appropriate action. To this effect, preliminary data has been generated from modeling studies and the index showed the top 20 countries contributing the most pollution [6,45]. GESAMP, which is an international advisory body on marine pollution, has carried out significant work to influence the decision-making process on microplastics [53].

Statutory requirements are one way in which governments can ensure compliance with standards. Although many cities have enacted by-laws restricting the use of plastics and their intentional fragments globally [9], a lot still needs to be done to bring global policymakers on board. A report by McKinsey Center for Business and Environment in conjunction with Ocean Conservancy has, thus far, given a systems approach to the problems of plastics, recommending a holistic approach that gives a five-point blueprint of questions to be asked and actions to be taken [173]. By 2016, about 69 plastics organizations and allied industry associations in 35 countries had signed an undertaking to make remediation efforts [174]. With regard to drinking water, the Global Research Global Coalition has also contributed to action plans which include investigation of retention of the plastics in drinking water and in WWTPs [44]. Overall, only when a critical mass of data has been generated on microplastics can a global solution be sought and implemented.

In view of all the challenges highlighted so far, there is a need for stakeholders to make concerted efforts to abate the environmental impacts of microplastics. Governments and other stakeholders can set aside funding linked to scientific research that can lead to reduced risks of microplastics entering water bodies depositing harmful chemicals which subsequently affect aquatic life and human health. For instance, the European Union launched projects aimed at standardizing analytical methods for the determination of microplastics in the aquatic environment [15]. The general public, as key stakeholders, have to be educated on the importance of cleaner environments. Leave-no-trace policies, including retrieving abandoned fishing and plastic gear, have been implemented in some coastal areas among other measures [175]. As such, communities can be encouraged to explore ways of managing plastic wastes through reuse, recycling and the recovery of resources in these materials for sustainable community development. This campaign needs budgetary prioritization to create an awareness of the risks associated with plastic litter in the environment that they live and depend on for water and food. Industry should perform life cycle analyses and look into alternative materials that are environmentally friendly through biodegradability pathways. In the design process, there is a need to reduce the amount of plastics materials used in making products. For example, by incorporating features such as ribs and curvatures, organizations can satisfy the utility requirements of products with a reduction in the wall thickness of products. Overall, this will minimize the volumes of plastics culminating in the environment and impacting both aquatic and human health. In addition to new product design, process, and equipment redesigning might be another option industry can explore to minimize the quantities of waste emitted into the environment. For example, instead of synthetic materials, the use of naturally occurring materials needs to be considered. Using biodegradable plastics in products such as cigarette filters will potentially reduce the volumes of microfibers found in resort beaches and other places. To decrease the quantity of plastics and microplastics emitted into the marine environment, an alternative approach is the adoption of the cost-effective reduce-reuse-recycle (3Rs) circular economy [28,29,52]. This circular economy approach is envisaged to be important in waste management over the next few decades.

9. Conclusion and Future Outlook

Being vectors for persistent organic pollutants and other micropollutants, microplastics potentially pose environmental and public health risks including interfering with the physiological processes of organisms when ingested and potentially causing ecotoxicity due to the inherent chemical additives. The ecological effects of microplastics are dependent on several factors, such as concentration, type, and age of microplastics, species and developmental stage of the bioassay species used, and the potential interactions of microplastics with organisms. These findings emphasize the need to conduct studies under environmentally and physiologically realistic conditions and consider various media and transfer pathways in assessing the ecological effects of microplastic exposure on aquatic environments.

To date, although evidence of risk at population level does not exist, there is a strong evidence-base for ecological risks of microplastics on some aquatic and terrestrial organisms, while that for human health risks remains weak. As an emerging research field, several knowledge gaps warranting further research were identified, including: (1) Better understanding of ecotoxicology of microplastics in humans including dose-response toxicity and behavior of microplastics in the human body, (2) interactions of microplastics with chemical contaminants and aquatic microbes, including the effects of biofilms on behavior and fate of contaminants on microplastics, (3) phase partitioning of microplastics and associated contaminants among solid and liquid components of aquatic systems such as various size fractions of sediments, pore water, aquatic plants, and other organisms such as fish, and (4) the degradation mechanisms and fate of microplastics along the transfer pathway from source into the human food chain is yet to be investigated. Addressing these knowledge gaps is critical for understanding the environmental and human health impacts, and development of mitigation measures to protect ecological and public health.

Coastal countries and countries in close proximity to large water bodies are vulnerable to the risks posed by microplastics. In order to ameliorate the ecological impacts associated with microplastics, a number of strategies can be taken. These include: (1) Because plastic residues are highly visible on the coastline, statutory requirements can be established making such areas prohibited zones for plastic debris. This can also be accompanied by campaigns aimed at disseminating information and incentivizing against plastic litter on the beaches; (2) alternative materials can safely and effectively be used to accomplish the same results as with microbeads; (3) industry can redesign their products, equipment, and processes to minimize the amounts of plastic used and hence decrease the plastic waste load that eventually finds its way into the environment; (4) to develop appropriate policy and management tools for mitigating the impact of microplastics on freshwaters in developing countries, there is need to consider shifting financial resources towards research, education and awareness to the wider population.

Further research should address knowledge gaps pertaining to the environmental health risks of microplastics, such as (1) the ecotoxicology of microplastics and how they interact with other pollutants in aquatic environments remain poorly understood; (2) little information is available on phase partitioning of microplastics and associated contaminants among aquatic components such as various size fractions of sediments, plants and other organisms such as fish; (3) the degradation and fate of microplastics along the transfer pathway from source into the human food chain is yet to be investigated, and (4) the sinking of microplastics in sediments due to the physical or biological phenomena requires detailed future study.

The bulk of studies on microplastics were drawn from developed countries, while literature from developing countries is scarce. Given the lack and/or poor enforcement of environmental legislation in developing countries, and the concomitant poor solid waste and wastewater management practices, the prevalence of microplastics in aquatic systems in these regions could be higher than initially thought. In these developing countries, where a considerable proportion of the population relies on untreated groundwater and open sources for drinking purposes, the human health risk could be potentially high.

Author Contributions: Conceptualization, N.C.; methodology, W.G., and N.C.; writing—original draft preparation, all authors; writing—review and editing, all authors; supervision, B.B.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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