Plastic wastes in the aquatic environment: ecotoxicological impacts and mitigation strategies

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ABSTRACT

Plastic products are in high demand due to their broad applications, resulting to a corresponding rise in the production of plastics. As a result of poor waste management practices such as uncontrolled open dumping, coastal littering, fishing, shipping and other industrial activities, plastics end up in the aquatic environment, where they accumulate as wastes. Recent studies on the abundance/concentration of plastic wastes in the aquatic environment and their resultant ecotoxicological impacts, as well as possible mitigation strategies were reviewed in this paper. Plastics do not decompose easily, and can break down into smaller particles known as nanoplastics (NPs) and microplastics (MPs) which are excellent vectors and sorbents of persistent organic pollutants, heavy metals and pathogenic microbes. NPs and MPs are easily distributed in the environment and also along trophic levels in the food web, and ultimately to humans, while their component chemicals/additives, which are mostly toxic, dissociate and accumulate in living organisms. Multiple studies reported the presence of significant amount of plastics in sediments, water and biota samples. Exposure of aquatic organisms to plastic wastes reportedly caused starvation, entanglement, suffocation, growth retardation, oxidative stress, cytotoxicity, reproductive and metabolic disorders, damage of the digestive tract, mortality, etc. They also induced apoptosis, affected the metabolism of sex hormones, and increased the risk of cancer and metabolic disorder in humans. Proposed mitigation strategies for plastic pollution include recycling and conversion of plastic waste to energy and value-added products, regulations of usage, reduced usage, bans, use of biodegradable plastics, and public awareness programs.

Keywords: Plastic wastes, Aquatic pollution, Marine plastics, Microplastics, Nanoplastics, Ecotoxicology, Waste management

1. Introduction

An aquatic environment can be defined as an interacting system of living and non-living elements in a freshwater or saltwater body. A healthy and conducive environment is very vital to the growth and survival of organisms living in it. Aquatic pollution has resultant adverse effects on the ecosystem and poses a serious environmental concern Nwaichi & Ntorgbo, 2016). Pollution caused by plastic wastes has been drawing global attention in recent years.

Plastics have broad applications; it is used in making food packaging, medical tools, electronics, tables, chairs, cutleries and other household items, and also in the construction,

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transportation and textile industries, among others. Therefore, the use of plastic products has been increasing for decades leading to a corresponding rise in the production of plastics. A significant portion of these plastics have single-use or short-lived applications; hence, they are quickly discarded as wastes (Yadav *et al.,* 2020). This has resulted in the production of more than 8.3 billion tonnes of plastic wastes since the 1950s (Veropalumbo *et al.,* 2023). According to Plastics Europe (2019), 359 million tonnes of plastics were manufactured globally in 2018 and this rate doubles approximately every 10 years. Also, an estimated annual production of 1 trillion tonnes of plastic bags globally has been reported (Harrison *et al.,* 2018a). The COVID-19 pandemic has also considerably contributed to the rise in plastic waste generation, due to the increased use of personal protective equipment such as single-use face masks and hand gloves. It has been reported that approximately 129 billion face masks and 65 billion plastic gloves are being used and discarded monthly worldwide (Aragaw and Mekonnen, 2021).

As a result of poor waste management practices (Fig. 1), which includes open dumps, coastal littering, inefficient filtration of smaller particles in wastewater treatment plants, industrial, domestic, fishing and shipping activities, etc., many of these plastics produced are lost to the environment conveyed by wind, flooding, leaching, surface runoffs, inland waterways, animals and humans; thus, about 12 million tonnes of plastic wastes leak into the oceans annually (Ryberg *et al.,* 2019; Yadav *et al.,* 2020; Alkimin *et al.,* 2022; Yadav *et al.,* 2022; Veropalumbo *et al.,* 2023). Approximately 9.2 million tonnes of plastics were lost to the environment in 2015 (Ryberg *et al.,* 2019).

Fig. 1: A roadside garbage dump in Lagos, Nigeria, comprising mostly of plastic debris

Plastic pollutants are particularly problematic because they do not decompose easily. Plastics are made up of a variety of compounds such as polymers, plasticisers and dyes which have potential hazardous effects (Enyoh *et al.,* 2022). In the environment, plastics not only cause significant damages to aquatic life, but also to human health and the tourism industry (Yadav *et al.,* 2022). Plastics have the ability to deteriorate and break down into smaller particles known as nanoplastics (NPs) and microplastics (MPs). Nanoplastics have particle sizes of 0.1μm or less (Gigault *et al.,* 2018); while, that of microplastics are between 0.1μm-5mm. Plastics with particle size greater than 5mm are often referred to as macroplastics (Yadav *et al.,* 2020). MPs can be classified based on their sources, which could be primary or secondary. Primary MPs are those intentionally produced to be less than 5mm for specific domestic or industrial purposes, or pellets accidentally formed as wastes during plastic production (Ryberg *et al.,* 2019). While, secondary MPs are derived from the breakdown of larger plastic materials by physicochemical forces such as water, sunlight, wind, heat, UV light and oxidation; mechanical forces and biodegradation (Auta *et al.,* 2017; Ryberg *et al.,* 2019; Peng *et al.,* 2020).

Due to their small sizes and large surface-to-volume ratio, NPs and MPs are easily distributed in the environment and along trophic levels in the food web; they are excellent vectors and sorbents of other pollutants such as persistent organic pollutants (Zhang *et al.,* 2015; Chen *et al.,* 2019) and pathogenic microbes (Peng *et al.,* 2020); they could also migrate through animal tissues and their component chemicals/additives are rapidly released (Maes *et al.,* 2017; Peng *et al.,* 2020). A rise in the concentration of NPs and MPs in the ecosystem increases the probability of their interaction and ingestion with/by organisms, which results to harmful consequences across the food web (Enyoh *et al.,* 2022a). According to UN Environment Programme (2018), the global annual loss of microplastics and macroplastics was estimated at 3.0 and 5.3 million tonnes respectively in 2015.

Babayemi *et al.* (2018) reported that less than 12% of plastic wastes in Nigeria are being recycled; the rest end up in landfills and dump sites and may also be disposed by open burning, which causes air pollution. Unless significant breakthrough in the management of plastic design or waste is achieved, plastic emissions are projected to increase in the future; and this could impact ecological processes or the global carbon cycle (Filella *et al.,* 2021). Hence, creating proper and improved plastic wastes management solutions has become a common global interest (Kawai *et al.,* 2022). Although, previous articles have been published in the past regarding the impacts of plastic pollution on the aquatic environment, this paper presents a concise review of recent studies on the abundance/concentration of plastic wastes in the aquatic environment, the toxicological impacts of plastic wastes on aquatic biota and humans, and potential solutions to plastic pollution issues.

2.1 Plastics: Definition, Types, Uses and Properties

Plastics can be defined as a group of synthetic, semi-synthetic or naturally occurring materials composed of organic polymers. They have the ability to be moulded into various shapes when softened by heat and pressure and retain these new shapes when hardened. The emergence of plastics began in the nineteenth century through a series of research carried out by a number of scientists. However, the first fully synthetic plastic (Bakelite) was produced in 1907 by Leo Baekeland. Plastics can be divided into two types; namely, thermoplastics and thermosetting plastics.

Thermoplastics are those plastics which become soft when heated and hard when cooled and have the ability to be shaped and reshaped by application of heat and pressure. Thus, they have the advantage of being remoulded and reused multiple times, and are more common than thermosetting plastics. Thermoplastics include polyethylene (for making plastic bags, wraps, bottles, etc.), polypropylene (for bottles, fibres and microwavable containers), polystyrene (for Styrofoam cups, test tubes and some medical devices), polyvinylchloride (for drain pipes, electric insulation, synthetic leather, food wraps and bottles), polyethylene terephthalate (for soft drink bottles, polyester fibre and production of fibreglass), polytetrafluoroethylene or

Teflon (for non-stick surfaces, plumbing tapes and chemical-resistant containers), etc. (Science History Institute, n.d.).

Thermosetting plastics (also known as thermosets) are those plastics that become permanently rigid and set when heat is applied. They can only be moulded once and cannot be softened and reshaped on further application of heat; rather they become damaged when exposed to high temperature conditions. Thermosets include polyurethane (for fibres and foams), Bakelite (for electrical cases, laminates, etc.), vulcanised rubber, epoxy resins, vinyl ester resins, etc. (Science History Institute, n.d.).

Although, each plastic has its unique characteristics depending on their chemical composition and method of processing, most plastics share some general properties. Plastics have low thermal conductivity, thus they are good insulators of heat and electricity. Some are transparent, while others have variety of colours with the addition of suitable pigments. Plastics are highly resistant to chemicals, solvents and moisture (resistant to corrosion); however, the degree of chemical resistance of each plastic varies based on their chemical composition. Plastics have low ductility which could result to spontaneous deterioration of their structural components. They have light weight and low processing cost and are quite durable. Thus, plastics have broad applications. Also, most plastics have low melting points (Susmita, n.d.). These general properties of plastics can be enhanced by additives, many of which are toxic and may leach into the environment (Helmenstine, 2020).

2.2 Degradability of Plastics

Plastics degrade very slowly; hence, they are likely to exist in the environment for a very long period of time. They tend to break down into MPs and NPs before being decomposed completely (Peng *et al.,* 2020). Some plastics undergo degradation under physicochemical conditions such as exposure to oxidation, hydrolysis, wind, sunlight and waves (Filiciotto and Rothenberg, 2021). Plastics that are degraded via oxidation are known as oxo-degradable plastics (e.g. oxo-degradable polypropylene); those oxidised by ultraviolet light are called photodegradable plastics and are a sub-category of oxo-degradable plastics; while, those degraded by hydrolysis are called hydro-degradable plastics e.g. polyacrylamide (Filiciotto and Rothenberg, 2021). Oxo-degradable plastics are usually conventional polymers mixed with pro-oxidant and antioxidant additives, while hydro-degradable plastics are often composed of a combination of petro-based plastic with a natural polymer like starch and/or cellulose; both plastics are usually non-biodegradable (Viera *et al.,* 2020; Filiciotto and Rothenberg, 2021).

Some plastics have the ability to decompose on exposure to certain microorganisms and enzymes under certain environmental conditions, and are known as biodegradable plastics. Examples include polyhydroxyalkanoates and polylactic acid (Filiciotto and Rothenberg, 2021). Different types of plastics exhibit varying degrees of biodegradation. Harrison *et al.* (2018a) defined a biodegradable compound as that which is completely used as a source of carbon for microbial growth. Degradation of such compound yields CO_2, water, inorganic salts and new biomass under aerobic conditions, and/or low molecular mass acids and methane under anaerobic conditions (Harrison *et al.,* 2018a). Plastics that cannot be decomposed by microorganisms and enzymes are said to be non-biodegradable.

Bio-based plastics known as bio-plastics are now being produced. The components of these bio-plastics are derived from renewable raw materials such as starch, cellulose, vegetable oils, wood chips, straw, food wastes, etc. Typical examples of bio-plastics are polyhydroxybutyrate and polylactic acid, both of which are biodegradable (Bahl *et al.,* 2020). It is important to note that the degradability of a plastic depends on its characteristics, which include the functional group, chemical structure and molecular weight of the polymer, and its additives; and not all bio-based plastics are biodegradable. Though, biodegradation of plastics can reduce the accumulation of plastic wastes, it is a slow and expensive process (Kumar *et al.,* 2021). Furthermore, compared to conventional plastics, biodegradable plastics (and also bio-plastics) have higher costs of production, low resistance and reduced mechanical properties (Martin *et al.,* 2014; Harrison *et al.,* 2018a). Also, degradation of oil-based bio-plastics may result in CO_2 emissions which contribute to global warming (Susmita, n.d.).

2.3 Sources of Plastic Wastes in the Environment

According to Ryberg *et al.* (2019), the largest source of plastics being lost to the environment is from mismanaged municipal solid waste (MSW) management such as uncontrolled open dumping and landfilling; other sources include industries like the cosmetic, textile, construction and transportation industries, and also from fishing activities. This may result from microbeads in cosmetic and personal care products, microfibers in waste water used in washing synthetic textiles, abrasion of tyre and road markings, and loss of fishing nets and ropes (Ryberg *et al.,* 2019), as well as shipping activities. A study done by So *et al.* (2018) in Hong Kong coastal water reported that 60% of samples contained plastic microbeads, which accounted for 3.6% of total microplastics collected from the water. The study suggested that the microbeads probably originated from cosmetics and personal care products sold in that area (So *et al.,* 2018).

The excessive use of polyethylene shopping bags and the packaging of products in plastic sachets also constitute a major reason for the prevalence of plastic wastes in the environment. Majority of macroplastics loss were recorded in regions such as Africa, Asia, Latin America and Caribbean with large number of low and lower middle-income countries and open dumps in a study (Ryberg *et al.,* 2019). This could be as a result of the low-income countries' inability to afford advanced plastic waste management techniques (Kehinde *et al.,* 2020). For instance, plastic litter makes up about 20% of total waste in Nigeria and 53% of products are packaged in plastics (Akinola *et al.,* 2014); also, the country is responsible for about 0.13-0.34 million metric tonnes of plastic marine debris yearly (Jambeck *et al.,* 2015).

Dumbili and Henderson (2020) cited the high consumption of plastic *sachet water* (also called *pure water*) which is the main source of potable water in Nigeria as a major cause of plastic pollution. These plastic sachets of water have single-use and are non-biodegradable, but they are in high demand due to their affordability and insufficient provision of safe drinking water by the government. Therefore, about 60 million plastic sachets are being used and disposed daily in Nigeria; and their indiscriminate disposal could result to blockage of drainages, air pollution (via burning of the plastic sachets) and aquatic pollution (Dumbili and Henderson, 2020). Approximately 9,258 tonnes of plastic sachet water wastes and 5,358 tonnes of other plastic wastes were generated in Abuja, Nigeria in 2012 (Ayuba *et al.,* 2013).

It has been discovered that several companies around the world market their non-biodegradable plastic products such as plastic bags and straws, under the guise of biodegradable in order to attract consumers; a practice termed "greenwashing" (Nazareth *et al.,* 2019; Viera *et al.,* 2020). Such greenwashing practices are misleading and harmful because they could encourage improper disposal of these plastic products by unsuspecting consumers; thereby, increasing plastic pollution.

2.4 Chemicals and Additives in Plastics

Plastics are manufactured using various chemicals and additives such as bisphenol A (BPA), polybrominated diphenyl ethers (PBDEs), bis (2-ethylhexyl) phthalate, triclosan, polybrominated biphenyls (PBBs), nonylphenol, polybrominated phenols (PBPs), etc. (Kumar *et al.,* 2021). BPA serve as a precursor/stabiliser; brominated organic compounds such as PBDEs, PBBs and PBPs act as flame retardants in the fabrication of electrical appliances; bis (2-ethylhexyl) phthalate is used as plasticiser; while triclosan is a biocide (Hahladakis *et al.,* 2018; Kumar *et al.,* 2021). Plastics have also been reported to act as vectors for chemicals and hydrophobic organic contaminants such as polychlorinated biphenyls (Chen *et al.,* 2019), polycyclic aromatic hydrocarbons and organochlorine pesticides (Zhang *et al.,* 2015), and also heavy metals (Enyoh *et al.,* 2022b), which are absorbed from the environment (Kumar *et al.,* 2021). Many of these chemicals have been found to be toxic. For instance, BPA, nonylphenol, phthalates and the brominated or chlorinated flame retardants are regarded as endocrine disrupting chemicals (Hahladakis *et al.,* 2018; Kumar *et al.,* 2021).

3.1 Plastic Wastes in the Aquatic Environment

Plastic wastes are found to be ubiquitous and persistent in the environment. Marine plastic pollution was identified as one of the top 10 emerging global environmental issues by the UN Environment Programme (2014). Multiple studies have reported the entry and accumulation of plastic wastes in the aquatic environment (Table 1). About 4.8-12.7 million tonnes of plastics leaked into the ocean in 2010 (Loubet *et al.,* 2022); approximately 15-51 trillion pieces of plastics weighing 93,000-236,000 tonnes were discovered in the ocean in 2015 (Van Sebille *et al.,* 2015); while that of 2016 was 19-23 million tonnes (Borrelle *et al.,* 2020). More than 8 million tonnes of plastics enter the ocean annually (UN Environment Programme, 2017; Peng *et al.,* 2020). Enyoh *et al.* (2019) reported that plastics made up 59% of total marine debris collected from five rivers in South Eastern Nigeria, with abundance of microplastics ranging from 440-1,556 particles/L. According to The United Nations Sustainable Development Goals Report (2022), more than 17 million metric tonnes of plastics entered the ocean in 2021; this accounted for 85% of marine litter and is estimated to double or triple by 2040.

These plastic wastes enter the aquatic bodies from land-based sources such as landfills, sewage, solid waste disposal, industrial effluents and surface runoffs; disposal of plastic wastes from ships (Kehinde *et al.,* 2020), commercial fishing (Watt *et al.,* 2021) and coastal tourism activities (Maione, 2021). Approximately 10% of marine plastic pollution is contributed by dumped fishing wastes and about 640,000 tonnes of discarded fishing gears (like old fishing nets, lines and traps) are abandoned in the ocean annually (Watt *et al.,* 2021). Plastic wastes (comprising of shopping bags, rubbers, flip flops, fishing gears, etc.) accounted for 48.5% of litter found in four coastal tourism sites in Zanzibar, Tanzania (Maione, 2021). Another study done at Talim Bay, Philippines by Paler *et al.* (2019) reported that plastic debris made up 85% of total litter on the beach. Plastic sachets which are commonly used as packaging materials in the Philippines were the most abundant plastic litter found in the study (Paler *et al.,* 2019).

Plastics which have similar densities with water tend to float on water surface; however, some MPs settle to the bottom of the ocean (Peng *et al.,* 2020). Studies have reported positive association between the concentration of MPs in seawater and sediments (Zheng *et al.,* 2019) and also higher abundance of MPs in sediments than in water (Song *et al.,* 2019). Yahaya *et al.* (2022) reported an abundance of MPs particles in Badagry lagoon ranging from less than 100-5000µm in size, with higher concentration of MPs recorded in sediments (283–315 particles/kg) than in surface water (108–199 particles/L). Olarinmoye *et al.* (2020) found microplastics in Lagos lagoon ranging from 310–2319 particles/kg and 139–303 particles/L in sediment and water respectively. Aquatic environments polluted with plastic wastes look and smell unpleasant and negatively impacts the tourism and fishing industries.

Table 1: Abundance/Concentration of Plastics in Selected Aquatic Habitats

Location	Sample	Plastic Particle Size	Abundance/ Concentration	Reference
Badagry Lagoon, Lagos, Nigeria	Surface water Sediment	<100-5000µm	108–199 p/L 283–315 p/kg	Yahaya *et al.* (2022)
Guanabara Bay, Brazil	Seawater	0.3-1mm	1.4-21.3 p/m^3	Olivatto *et al.* (2019)
Lagos Lagoon, Nigeria	Sediment Water	125-500µm >1000µm	310–2319 p/kg 139–303 p/L	Olarinmoye *et al.* (2020)
Lagos, Nigeria	Beach sand	-	3424 p/m^2	Fred-Ahmadu *et al.* (2020)
Arctic Central Basin	Sediment	<5mm	0-200 p/kg	Kanhai *et al.* (2019)
Braamfontein Spruit, Johannesburg, SouthAfrica	Stream Sediment	-	705 p/m^3 166.8 p/kg	Dahms *et al.* (2020)
Five rivers in Nwangele, Imo State, Nigeria	Water	-	440-1,556 p/L	Enyoh *et al.* (2019)
Northwestern Pacific	Seawater	-	0.13±0.11 p/m^3	Mu *et al.* (2019)
Eleko, Lekki, Alpha and	Surface Sediment	-	Eleko: 170±21 Lekki: 141±36	Ilechukwu *et al.* (2019)

Oniru Beaches in Lagos, Nigeria			Alpha: 133±16 Oniru: 121±38 (particles/50g sample)	
Tamil Nadu Coast, India	Beach sand	0.3-4.76mm	46.6±37.2 p/m^2	Karthik *et al.* (2018)
Ziway, Ethiopia	Sediment	-	400-124,000 p/m^3	Merga *et al.* (2020)
Southern North Sea	Sediment	0.011-0.5mm	2.8-1188.8 p/kg	Lorenz *et al.* (2019)
Arctic Central Basin	Seawater	1-2mm	0.7 p/m^3	Kanhai *et al.* (2018)
Northeast of Algeria	Sediment	-	182.66±27.32 to 649.33±184.02 p/kg	Tata *et al.* (2020)
North Yellow Sea, China	Seawater	<0.5mm	545±282 p/m^3	Zhu *et al.* (2018)
Malaysian Marine Waters:				Khalik *et al.* (2018)
Kuala Nerus Beach, Terengganu	Surface water	<5mm	0.13-0.69 p/kg	
Kuantan Port, Pahang	Surface water	<5mm	0.14-0.15 p/kg	
Slovenian Beaches	Beach sand	<5mm	0.5±0.5 p/kg (March) 1.0±0.8 p/kg (August)	Korez *et al.* (2019)
South Funen Archipelago, Baltic Sea	Seawater	0.3-0.63mm	0.07±0.02 p/m^3	Tamminga *et al.* (2018)

*p/m^3, p/kg, p/L, and p/m^2 represents plastic particles per cubic metre, particles per unit mass, particles per litre and particles per square metre of samples respectively

Plastic particles have also been found in various aquatic organisms (Table 2). Adeogun *et al.* (2020) reported the presence of microplastics in the stomach of seven out of eight commercial fish species collected from Eleyele lake in Nigeria; with the highest prevalence (34%) recorded in *Oreochromis niloticus*. 73.3% of freshwater fish species sampled in Bangladesh had MPs in their gastrointestinal tracts; with *Mystus vittatus* having the highest abundance of MPs out of all the fish species examined in the study (Parvin *et al.,* 2021).

Table 2: Abundance/Concentration of Plastics in Some Aquatic Organisms

Location	Sample	Plastic Particle Size	Abundance/ Concentration	Reference
Eleyele Lake, Oyo State Nigeria	Fish species	124µm-1.53mm	1-6	Adeogun *et al.* (2020)
Sanggou Bay, China	Oysters	0.05-5mm	41±15.5	Wang *et al.* (2019)
Eastern Central Atlantic Ocean, off the Coast of Ghana	Fish species	-	40±3.8 to 25.7±1.6	Adika *et al.* (2020)
Coastal areas of China	Oysters	<1.5mm	2.93	Teng *et al.* (2019)
KwaZulu-Natal, South Africa	Fish species	0.89±0.77mm	0.79±1	Naidoo *et al.* (2020)
Northern part of the Persian Gulf	Mollusc	0.01-5mm	3.7-17.7	Naji *et al.* (2018)
Braamfontein Spruit, Johannesburg, SouthAfrica	*Chironomus sp.* larvae	-	53.4 (p/g)	Dahms *et al.* (2020)
Australian urban wetlands	Fish (*Gambusia holbrooki*)	-	0.1	Su *et al.* (2019)
Alexandria, Egypt	Fish	-	28-7527	Shabaka *et al.* (2020)
Guangxi Beibu Gulf, China	Indo-Pacific humpback dolphins (*Sousa chinensis*)	1-5mm	0.2-0.8 (p/g)	Zhu *et al.* (2019)

*p/g represents plastic particles per gram of sample. Other figures in the abundance column are represented as plastic particles per individual organism.

Fig.2: Plastic debris in the stomach of a sea turtle found in the Pacific Ocean, according to The Ocean Cleanup Foundation (Reddy, 2018).

3.2 Toxicological Effects of Plastic Wastes on Aquatic Biota

Several studies have shown that plastic pollutants exert toxic effects on aquatic biota (Table 3). Additives used in plastic production can potentially dissociate from plastic products and accumulate in living organisms (Koelmans *et al.,* 2016). For example, PBDEs were detected in *Puffinus tenuirostris* (Bakir *et al.,* 2014) and mono-2-ethylhexyl phthalate was found in *Cetorhinus maximus* (Fossi *et al.,* 2017). Many of these additives may be mutagenic and carcinogenic, and may also adversely affect animal reproduction (Mathieu-Denoncourt *et al.,* 2015; Rillig and Bonkowski, 2018). Toxic microbes may also adhere to plastics and act as disease vectors in the marine ecosystem (Osborn and Stojkovic, 2014; Harrison *et al.,* 2018b). Some marine animals mistake plastic substances as food and ingest them (Fig.2). The ingested plastics then accumulate in the organisms and are transferred along trophic levels of aquatic feeding relationships and ultimately to humans. They could cause adverse effects such as starvation, reduced growth rates, oxidative stress, lipid peroxidation and damage of the digestive tract which could lead to mortality (Lavers *et al.,* 2014; (Fossi *et al.,* 2016; Nichols *et al.,* 2021).

Aquatic organisms may also become entangled in plastics such as discarded fishing gears, plastic bands and packaging materials; this could restrict the movement of these organisms and also result to injury, suffocation and death (Fig.3). Plastics also transport invasive species and other contaminants, and this poses risks for biota and humans via direct or indirect exposure to these plastics ((Fossi *et al.,* 2014; Lehner *et al.,* 2019; Oliveira and Almeida, 2019; Nichols *et al.,* 2021). According to Kumar *et al.* (2021), micro- and nanoplastics delay cellular transformation, diminishes the rate of physical development and reduces organ regeneration capacity.

Fig.3: A plastic band wrapped around a blue-striped grunt fish in the Caribbean Sea (Ingelsson, 2021).

Pedersen *et al.* (2020) discovered that exposure of zebrafish (*Danio rerio*) to nanoplastics resulted in a dose-dependent effect on neurobehaviour and metabolism. Another study showed that NPs triggered oxidative stress and upregulation of apoptopic genes in Caribbean swamp oysters, *Isognomon alatus* (Arini *et al.,* 2022). Tang *et al.* (2018) observed increased oxidative stress, inflammation of the immune system and impaired detoxification in *Pocillopora damicornis* exposed to polystyrene in natural seawater. Seabirds, *F. glacialis* and *Ardenna grisea* which were found either dead or stranded on beaches had macro- and microplastics in their gastrointestinal tracts, which caused obstruction of their digestive tracts, congestion of the ventricles and eventually death of the animals (Terepocki *et al.,* 2017). Studies have also reported that MPs and NPs induced growth retardation and damages in *Pomatoschistus microps* (Ferreira *et al.,* 2016; Steer *et al.,* 2017); and also cytotoxicity and decreased feeding and phagocytic activities in the bivalve, *Mytilus edulis* (Wegner *et al.,* 2012; Canesi *et al.,* 2015).

MPs may be responsible for gut inflammation and reduced immunity in *Arenicola marina* (Browne *et al.,* 2013; Green *et al.,* 2016); could trigger allergic immunological responses in the blood stream (Santillo *et al.,* 2017); and may also cause reproductive defects (Cole et al., 2015; Dobson et al., 2017) in aquatic organisms. Ribeiro *et al.* (2019) observed that NPs accumulated in brain tissues of *C. carassius* was responsible for brain damage and behavioural disorder in the fish. Increase in MPs and NPs concentration resulted in a decrease in shoot length of Eurasian water milfoil (*Myriophyllum spicatum*) in a study by Van Weert *et al.* (2019). The study also reported that nanoplastics reduced the shoot to root ratio of *M. spicatum* and *Elodea sp.* (water weed).

Table 3: Toxicological Effects of Plastics on Aquatic Organisms

Sample	Class of Plastic (by size)	Effects	Reference
Zebrafish (*Danio rerio*)	Nanoplastics	Neurobehavioural and metabolic disorder	Pedersen *et al.* (2020)

Scleractinian Coral, *Pocillopora damicornis*	Microplastics	Increased oxidative stress, inflammation of the immune system and impaired detoxification	Tang *et al.* (2018)
Zooplankton	Nanoplastics	Decreased the survival of zooplankton.	Mattson *et al.* (2017)
Fish		Initiated behavioural disorders in fish.	
Caribbean swamp oysters (*Isognomon alatus*)	Nanoplastics	Triggered oxidative stress and upregulation of apoptopic genes	Arini *et al.* (2022)
Oyster	Nanoplastics	Caused reproductive disorders, impaired fertilisation and embryonic development	Tallec *et al.* (2018)
Seabirds, *F. glacialis* and *Ardenna grisea*	Macro- and microplastics	Caused obstruction of digestive tracts, congestion of the ventricles and mortality	Terepocki *et al.* (2017)
Fish (*C. carassius*)	Nanoplastics	Initiated brain damage and behavioural disorder	Ribeiro *et al.* (2019)
Bivalve, *Mytilus edulis*	Nanoplastics	Decreased phagocytic activity, induced cytotoxicity and increased lysozymal activity	Canesi *et al.* (2015)

4. Implications of Plastic Wastes on Human Health

Plastic wastes can be broken down into MPs and NPs which can be found in seafood. MPs have been found in some gastropods (Akindele *et al.,* 2019), several fish species (Adeogun *et al.,* 2020) and also in table salts and water (Verla *et al.,* 2019). The average daily consumption of fish muscle by humans was estimated at about 7g per individual (Peng *et al.,* 2020). Humans can be exposed to MPs and NPs via ingestion of contaminated food and water and also inhalation of contaminated air and aerosols (Prata *et al.,* 2020; Kumar *et al.,* 2021). About 0.40–2.40 particles/L MPs were found in freshwater samples of Chao Phraya and Maeklong Rivers in Bangkok, designated for tap drinking water production; MPs were also detected in treated tap water samples, which suggests potential contamination from the freshwater sources (Chanpiwat and Damrongsiri, 2021). According to Abbasi *et al.* (2018), an average of about 5 pieces of MPs could be taken up by humans daily. Prata *et al.* (2020) stated that every person in Portugal may ingest 1440 MPs a year through the consumption of molluscs, as the citizens are highly reliable on seafood.

Because plastics are very stable, they could accumulate and may potentially cause long-term damages to human health (Peng *et al.,* 2020). These plastic particles enter the blood vessels and form a protein-plastic complex which enables them to evade the human defence system and exert geno- and cytotoxicity (Gopinath *et al.,* 2019). Studies have reported that in human, MPs and NPs exposure induced oxidative stress (Ruenraroengsak and Tetley, 2015; Pedersen *et al.,* 2020) and apoptosis (Inkielewicz-Stepniak *et al.,* 2018), hindered iron transport (Mahler *et al.,* 2012), influenced the up-regulation of cytokines (Forte *et al.,* 2016) and adversely affected the metabolism of sex hormones (Mathieu-Denoncourt *et al.,* 2015). BPA, a chemical constituent of plastics is said to increase the risk of prostate and breast cancer, polycystic ovarian syndrome, recurrent miscarriages, endometrial hyperplasia, obesity and metabolic disorders (Kehinde *et al.,* 2020).

Burning of plastic wastes contributes to global warming and air pollution through the release of soot, greenhouse gases and toxic chemicals such as polychlorinated biphenyls, dioxins, furans and mercury which are hazardous to human and biota, and also negatively affects water, soil and air quality (Verma *et al.,* 2016; Ogundairo *et al.,* 2021).

5.0 Mitigation Strategies for the Control of Plastic Wastes in the Aquatic Environment

The proliferation of plastic wastes in the aquatic environment can be mitigated by controlling their anthropogenic and land-based sources. Improvement of waste management systems will significantly reduce plastic wastes in the environment (Prata *et al.,* 2020). According to Nyakuma and Ivase (2021), the Reduce, Reuse and Recycle (3Rs) concept can be employed as a sustainable approach for plastic waste management. This approach comprises various techniques for collecting, storing, segregating, processing, transporting, treatment or disposal and reuse of plastic wastes in a cost-effective, innovative and eco-friendly manner, thus, reducing the volume of plastics wastes (Nyakuma and Ivase, 2021). The following strategies can be used to control plastic pollution:

5.1 Recycling and Conversion of Plastic Wastes to Value-Added Products:

Recycling is widely acclaimed as one of the most efficient method of plastic waste management (Kehinde *et al.,* 2020; Kumar *et al.,* 2021). Establishment of adequate number of used plastics reception and recycling facilities in various towns and cities, especially in underdeveloped and developing countries, where people return their used plastics and receive incentives as a token of encouragement, would go a long way to reduce illegal dumping of plastics. The government should introduce and enforce penalties for indiscriminate plastic waste disposals by individuals, groups or industries. In 2019, Japan issued the "Resource Circulation Strategy for Plastics", which is targeted at promoting the recycling of plastics; the strategy includes ensuring that 60% of plastic packaging materials and containers are reused or recycled, the quantity of recycled resin used in manufacturing products are doubled by 2030; and also ensuring 100% utilisation rate and energy recovery of all plastic wastes by 2035 (Kawai *et al.,* 2022). This was shortly followed by the enactment of the "Law for Promotion of Resource Circulation of Plastics" in 2021 (Kawai *et al.,* 2022).

Recycling of plastic wastes offers some economic benefits and entrepreneurial opportunities. Through recycling, plastic wastes are converted into value-added products with reduced cost of production and better quality. For instance, in the construction industries, plastic wastes can be added to cement mixtures to enhance their physical and mechanical strength; they can be added to bitumen and aggregates for road construction to reduce moisture absorption and permeability of the road and thereby improve the quality of the road; they can also be used as soil stabilisers to improve the geotechnical properties of the soil (Manju *et al.,* 2017; Kehinde *et al.,* 2020; Ogundairo *et al.,* 2021). Plastic wastes can be incorporated into brick making to produce eco-friendly bricks with adequate compressive strength, and also in concrete reinforcement to produce concrete structures with improved strength, stability and durability and reduced corrosion (Foti, 2016; Kamaruddin *et al.,* 2017; Ogundairo *et al.,* 2021; Aneke and Shabangu, 2021). Several novel technologies for the conversion and valorisation of plastic wastes have been proposed. These include the conversion of plastic wastes into carbon nanomaterials, polymers and composite materials, solvent/solvothermal treatment and plasma conversion (Nyakuma and Ivase, 2021). The use of plastic wastes in artistic creations has also been reported (Wagner-Lawlor, 2018; Asamoah *et al.,* 2022). Furthermore, they can be used in producing textiles (Kehinde *et al.,* 2020). Therefore, the plastic waste management industry can also serve as a means of wealth creation.

5.2 Reduced Plastic Usage, Introduction of Bans, Regulations and Levies:

While, it may be difficult to completely avoid the use of plastics, people should always make conscious efforts to reduce plastic consumption by using them only when necessary; utilise only reusable plastics and avoid single-use plastics; and also endeavour to reuse plastic containers and packaging materials in their possessions. Prata *et al.* (2020) suggested that microplastics pollution can be alleviated by reducing the discharge of untreated wastewater, banning the use of microbeads in cosmetic products and continuous monitoring of freshwater environments. Several countries have put forward measures to curb plastic pollution. These measures include regulation of the use of plastic products through the placement of bans on plastic bags (as done in Kenya) and non-reusable plastics, or taxes/levies on plastics (Dikgang *et al.,* 2012; Thomas *et al.,* 2016; Xanthos and Walker, 2017; Martinho *et al.,* 2017; Dumbili and Henderson, 2020). The USA and the UK banned the use of plastic microbeads in personal care products in 2015 and 2018 respectively (Kumar *et al.,* 2021).

5.3 Use of Biodegradable Plastics as Substitutes for Conventional Plastics:

As stated earlier in this paper, biodegradable plastics are those that can be degraded by microorganisms and enzymes under certain conditions. Replacing conventional plastic materials with biodegradable ones, and also ensuring proper disposal and management of biodegradable plastic wastes can help lessen plastic pollution. Single-use and non-biodegradable plastic products are found to be relatively cheaper than their reusable and biodegradable counterparts; hence, people are more inclined to consume single-use and non-biodegradable plastics. The government can help solve this problem by increasing taxes on the production and sales of single-use and non-biodegradable plastics, decreasing that of the reusable ones and subsidising the production costs of biodegradable plastics; this would help reduce the prices of reusable and biodegradable plastics, thereby making them more affordable for consumers.

5.4 Conversion of Plastic Wastes to Energy:

Plastic pollution can also be controlled through the conversion of plastic wastes to energy (Babayemi *et al.,* 2018). Plastics are produced primarily from energy feedstock like natural gas, oil or coal, which are composed of hydrocarbons; thus plastics can serve as a form of stored energy (Wang *et al.,* 2017; Ayodele *et al.,* 2019). Several studies have reported the possibility of converting plastic wastes to bio-oil and gas which are sources of energy, through pyrolysis (Çepelioğullar and Putun, 2013; FakhrHoseini and Dastanian, 2013; Ahmad *et al.,* 2015; Miandad *et al.,* 2017; Sharuddin *et al.,* 2018; Ayodele *et al.,* 2019). The pyrolysis of plastic wastes collected from selected cities in Nigeria generated 87.5MW of electricity in a study carried out by Ayodele *et al.* (2019). The result from the study however suggested that electricity generation from pyrolysis of plastic wastes may have corresponding environmental implications by initiating global warming and acidification (Ayodele *et al.,* 2019).

5.5 Public Education and Awareness Programs:

Creation of awareness campaigns via social media, commercials, publications and school activities on the dangers of plastic pollution; establishment of environmental clubs and organisation of beach clean-up events would also greatly help to reduce aquatic plastic pollution. This would induce positive behavioural changes and disposition in people towards the use of plastics and plastic waste disposal.

Conclusion

Mismanagement of plastic wastes and their slow decomposition rate has resulted to their large accumulation in the aquatic environment. They remain in the environment for long periods and exert toxicities to aquatic biota, human and the ecosystem. There is need to establish improved and efficient waste management systems to control aquatic plastic pollution. Reuse and recycling of plastic wastes, reduced usage, and use of biodegradable plastics among other strategies have been proposed to mitigate plastic pollution in the aquatic environment. Although, replacing conventional plastics with biodegradable ones can help alleviate the accumulation of plastic wastes, the latter has a higher cost of production and the biodegradation process is slow. Moreover, toxicity studies on the interaction of biodegradable plastics with other environmental contaminants are scarce. Hence, the public misconceptions that biodegradable plastics are completely eco-friendly and the consequent increased usage may encourage littering and improper waste disposal, which may cause more problems.

Therefore, further investigations on faster, cheaper, eco-friendly and sustainable biodegradation techniques, as well as the ecotoxicological effects of co-exposure of biodegradable plastics with other toxic chemicals in the environment are very essential. There is a need to develop a comprehensive framework for assessing the negative impact of plastic pollutants on ecosystem and human health. More studies are necessary to examine the sources and mechanism of bioaccumulation and biomagnification of plastic pollutants, and their exact effects in organisms. This will help guide decisions and actions towards the development of safe and sustainable solutions for plastic pollution problems. Recycling of plastic wastes offers entrepreneurial opportunities and economic benefits. Further research on value-added products that can be generated from plastic wastes under eco-friendly conditions, as well as the quality, stability and durability of these products should be carried out.

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