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Micro-plastics in Aquatic Environment: Source, Fate, Emerging Threats, and Regulatory Effort

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Presences of plastics in aquatic environment, and their possible cascading along the food chain are an environmental concern. To understand the current setup in plastics pollution, we submit the evolution of the plastics industry, the production process, and the magnitude of plastics produced and plastic waste generated. In the second section, we give an over view of sources of micro plastics in aquatic environment including; domestic, leisure, aquaculture, maritime activities and horticulture. Thirdly, we address the behavior and distributions of micro plastics in aquatics system (rivers, estuaries, lakes and ocean) and their matrixes (surfaces, water column, and sediments). In fourth section, we raise the insidious natures of micro plastics pollutions, as a threat to life, and, in the fifth section we identify the developments in policies that targets to mitigate plastic pollution.

Keywords: Plastic; micro plastics; rivers; estuaries; lakes; marine; policy.

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1. INTRODUCTION

The word 'Plastic' originates from the Greek word "plastikos" meaning "capable of being mounded". Fossil fuels are the main raw material for producing synthetic plastics, but natural sources such as biopolymers and mineral based (salt) accounts in smaller scale [1]. Distillation of crude oil in plastics production, involves a complex catalytic process, which cracks ethane and propane monomers, into ethylene and propylene polymers (a polymerization process), at high energy consuming furnace (over 800^{o}C). The end product is a powder that is used to make plastics pellets. Additives, (such as flame retardants, biocides, plasticizers, ultra violet (UV) stabilizers, antioxidants, colorants) are incorporated in plastics to enhance their functional and structural properties, making plastics to be light, durable and affordable. Thus plastics are versatile, and over time, they have replaced wood, stone, horns, bones, leather, paper, metal, glass, and ceramic, such that sometimes this age has been referred to as 'plastics age' [2].

Broadly, plastics are categories into thermosets and thermoplastics; thermosets undergoes chemical change when reheated, hence non-recyclable, but thermoplastics do not and thus recyclable. Examples of thermoplastics are; Polyethylene (PE), Polyamides (PA), Polypropylene (PP), Polycarbonate (PC), Polystyrene (PS) and Expanded polystyrene (EPS), Polyethylene terephthalate (PET) and Polyvinyl-chloride (PVC). Thermosets includes; Polyurethane (PUR), Silicone, Epoxy and Phenolic resins, and Acrylics. The most widely used types of plastics are polyethylene, polypropylene, polyvinylchloride, polyurethane, polyethylene terephthalate (PET), polystyrene and others at, 29.4%, 19.1%, 10.1%, 7.5%, 7.1%, 6.9%, 19.1%, respectively [3,4,5,1].

1.1 Growth of Plastics Industry

Use of natural rubber dates back in 1600 B.C., but the discovery of vulcanization, a rubber making process, resulted in commercial production of plastic in 1839. Bakelite, a total laboratory manufactured plastic from phenol-formaldehyde resin was produced in 1907, later followed rayon, a semi-synthetic plastic from cellulose in 1911. In 1930's most of the plastics were low density plastics, where Bakelite dominated, as an electrical and heat insulator, and novel product for jewels and button making. The Second World War stimulated a short lived increase in demand for plastics that could not be met from natural rubber. This created opportunities for mass production of synthetic rubber, to make tires and nylon ropes for military equipment's. Later, production of plastics increased from 9.2 million metric tons in 1950, to 370 million metric tons in 2019. A growth attributed to penetration of plastics in the industrial revolution, and the use of high density plastics in production of household goods. Today, plastics production consumes 4-6 percent of global oil and gas produced, which is expected to reach 20%, by 2050. Packaging, building and construction, and automotive industries are lead consumers of plastics at, 37.9%, 19.7%, 10% respectively [6,7,8,2,5]. China, North America and Europe are the lead plastics producing regions, at 31%, 21% and 20%, respectively, while Sri Lanka, U.S., South Africa, China and India, are lead per capita consumers at, 5.0 kg of plastic per day (kg/ppd), 2.59 kg/ppd, 2.0 kg/ppd, 1.10 kg/ppd and 0.34 kg/ppd, respectively, compared to 0.2 kg/ppd globally [6,9]. Annual global growth in demand for plastics stand at 9%, and it is estimated to reach 210%, and higher (375%) in Sub-Saharan Africa, Middle East and North Africa combined by 2060 [10].

In summary, the growth of plastic industry has been characterized by an initial slow growth from 1910 to 1950, a second exponential growth from 1950 to 2000, and a third linear positive growth corresponding to economic growth from 2000 [11,6].

1.2 Generation and Degradation of Plastic Waste

Globally, plastics contribute over 13% of municipal solid wastes, generating 275 million tons of plastic waste annually, where packaging accounts for 46%. Plastics can last over 500 years, and it is estimated of the 8.3 billion tons of virgin plastic ever produced, 2500 million tonnes (30%) are still in use, 4600 million tonnes (55 %) are in landfills or discarded, 700 million tonnes (8 %) have been incinerated and 500 million tonnes (6 %) recycled. In Europe, out of 17.8 metric tons of post-consumer plastic collected in 2019, about 42% were recycled, 39.5% used in energy recovery and 18.5% ended up in landfills. By 2050, about 12,000 metric tonnes of plastic will be in landfills or in the natural environment. The problem of plastic waste is expected to increase in Sub Saharan Africa, due to increasing use of plastics, poor waste management, and illegal dumping of plastic waste from developed countries. Recycling and circular economy in plastics industry can reduce generation of plastic waste, but the bulkiness and poor sorting of plastic waste makes recycling unprofitable, while undisclosed content of toxic additives, erodes confidence in safety in recycled plastics [11,12].

Most plastics are not bio degradable, but effort in developing bio degradable plastics continues. Bio degradable plastics are expensive, barely used, and only degrade under special industrial conditions. Large/mega (> 1m) plastics fragments can degrade to macro (25-1000mm), meso (5-25mm), micro (< 5mm) and nano (< 1 μm) particles. Weathering of plastics changes their chemical and physical properties, thus, becoming brittle and of low molecular weight [13]. The degradation rate is determined by; their inherent properties (such as crystallinity, molecular weight, their functional groups, and additives), physical forces acting on it (such as heating/cooling, and wetting/drying wave actions), and other environmental factors such as pH and exposure to ultraviolet (UV) light, and their interactions with microbe and oxidative agents [14,4,15,16,17,10,18].

1.3 Source of Micro Plastics in Water Bodies

Among plastics fragments, micro plastics (< 5mm) are the most dominate in the environment. Micro plastics are categorized into primary and secondary micro plastics, depending on their sources. Primary micro plastics; are purposefully produced as pellets/micro-beads for molding final plastics products, 3D printing, exfoliation in cosmetic products, blasting or cleaning industrial surfaces [16,4,5,10,18]. Secondary micro plastics; are intentionally/accidentally driven from; cutting, polishing or molding of plastic-based products, emissions from weathering of; plastic-based paints, wearing of synthetic textile fibers especially in laundries, and rubber tires in contact with road, and weathering of plastics items/waste [4,15,13,16,17].

Human activities that directly or indirectly introduces micro plastics in aquatic environment includes; laundry, aquaculture, maritime activities, and horticulture. Domestic laundries, industrial effluent, runoff especially from landfills, and storm water are the main contributors of micro plastics in waste water treatment plants (WWTP). Efficient reduction of micro plastics in a WWTP depends on the size of preliminary screen and the rate of sludge deposition. High density micro plastics that pass the screen, settles in the sludge, while suspended lighter particles are conveyed into receptor water body [18]. Fish farming and the supporting infrastructures uses plastics from nursery cages, water conveyance, pond lining and screening, fish cages, buoys, to packaging. Weathering and degradation of these plastics by; storm events, wave action, and Ultra Violet radiation, and destructions by cultured organisms' results in introduction of micro plastics in water bodies. Maritime activities such as coastal tourism, yachting, shipping and wearing out of sea vessels, contribute to marine plastic pollution, including accidental loss of microbeads from sea vessels [16].

Settling of atmospheric micro plastics pollution that originates from wearing out of vehicles tires, balloons, and plastic sports carpets adds to aquatic plastic pollution. While the use of plastics in horticultural technologies such as biofilms, plastics tunnels, plastics mulching and application of fertilizers and bio solid from waste water treatment plants (WWTP), also contributes. Accounting for all these sources in aquatic plastic pollution has not been clear [18].

2. MICRO PLASTICS IN WATER BODIES

2.1 Rivers

The size of a river (width, depth, length) and its catchment characteristic such as profile, hydrology, meteorology, human population density including industrial activities, influences its micro plastics load [19]. While water parameters such as temperature, oxygen, water density, and salinity, affect the transportation and distribution of micro plastics in rivers [20-23]. Riverbanks act as transient sources of plastic in rivers, due to changing water levels as occasioned by floods and drought. Dry seasons influence high deposition of micro plastics at river banks as a result of decline in water levels and its velocity, while flooding recollect these micro plastics as water levels increases and its velocity [18].

Horizontal and vertical redistribution of micro plastics in river waters depends on the degree of micro plastic degradation, sedimentation and resuspension rates, adsorption and aggregation, biofouling, ingestion and excretion by aquatic organism. However, there are areas that merit scientific investigation such as; inputs of micro plastics in rivers, deposition, and accumulation sites ("Hotspots"), exchange between riparian and benthic habitats, and export and accumulation rates at annual and seasonal scale [24,20,25].

Physio-chemical properties of micro plastic (such as density, shape, and size) are in continuous change, as they interact with changing water pH and salinity among others. These interactions affect the buoyancy/sinking, structure, polarity and hydrophobicity of micro plastics. Air trapped in micro plastics particles will reduce their density, and thus increasing their buoyancy, while interactions with sediments and microbe increase their density and therefore deposition rate. Common consumer plastics have a density ranging between 0.85 to 1.41 g/cm^3, a range that straddles the density of fresh water (1 g/cm^3). Some finished plastic products contain fillers of specific gravity as high as 3.0 g/cm^3. Meaning some micro plastics floats and others are deposited at the rivers bottoms. Thus, high density plastics tend to sink and transported as river bed load, sometimes settling as sediments, while low density plastics are transported in suspension within the water column. Higher levels of micro plastics have been reported at surface waters, than in river bank and bottom waters, while higher deposition along river banks, river bend, dams, flood plains and estuaries are common. River currents redistribute micro plastics, disrupting this equilibrium. However, few studies have been conducted to compare levels of micro plastic concentrations in water surface and subsurface, and their distributions in sediments [26,14,27,28,19,4,13].

2.2 Estuaries

At estuaries, inflowing, low density freshwater usually passes over an underflow of denser saline sea water, that moves toward inland source. This exchange generates eddy currents, which agitates and suspends deposited particles, creating a homogeneous mixture of micro plastics throughout the water column. This is more pronounced in shallow estuaries, high velocity inflows, and highly stratified lakes. However, overtime there is a natural gradient of higher deposits of micro plastics from inland sources towards the sea in calm waters. Spatial and seasonal distribution of micro plastics at horizontal and vertical scale can be influenced by water depth and its salinity gradient, and physical and chemical characteristics of the plastics [29,19].

2.3 Lakes

Sources of micro plastics in lakes and dams depend on their proximity to urban and industrial centers, and populations' density [21]. Therefore, urban lakes receive higher micro plastics load from inflowing streams draining residential, commercial and industrial areas. Wider dispersion of micro plastics occurs in larger lakes/dams, than in smaller lakes and dams. This is as result of high surface wind energy that generates waves and circulation currents, distributing micro plastics towards their direction [23]. Drifting of micro plastics on surface waters, water column or sinking to the bottom occur, at different scale. Suspended low density plastics are transported in higher levels and deposition at lake offshore, while minimal movement in the lake's bedload leads to accumulation of sinking micro plastics in sediments [23]. Preliminary studies indicate that water velocities and micro plastics aggregation with organic matter, microbes, and minerals results in increases particle density, affecting its location within the water column. Association of micro plastics with microbes, especially in shallow and high productivity lakes can increase their deposition [30].

Therefore, in lakes, areas of high micro plastics deposits include; those close to contaminant inflow (such as sewage sludge input from WWTP), entrance of fast-running rivers, and bottom sediments of small lakes that have long residence times. Other areas such as larger lake shore and flood plains that are exposed to long duration of water recession have high micro plastic loads, and those in front of weirs and dam walls [30].

2.4 Marine Waters

Initial highlights on marine plastics pollution were in 1970's, when presence of micro plastics at sea floor was reported. Later followed reports of plastic 'soup' in North Pacific central gyre in 1977, indicating Oceans as major plastic sinks from inland sources [31,32]. Pathways to marine plastic pollution include; runoff, rivers, and atmospheric flux (natural storms or high winds), rivers being the main contributors. About 10 to 20 million tons of plastics leak into the ocean annually, and this is expected to increase to 600 million tons by 2030. Inland sources accounts for 80% of marine plastics pollution, while maritime activities and atmospheric flux 20%. By 2050, oceans will contain more plastics than fish (by weight) [11,33,30]. About 5 trillion pieces of plastics float on ocean, but since half of all plastics are denser than seawater, they tend to sink to the seafloor, meaning a big percentage of marine plastic pollution is unaccounted for [14,4,15,16,34,17,10,13].

3. EFFECTS OF PLASTICS AND MICRO PLASTICS IN FRESH WATER AND MARINE ECOSYSTEMS

Micro plastics are distributed in all aquatic environment matrices including; river sediments, banks, sea floor, water columns and surface waters. The effects of internalization of micro plastics, and their associating toxic chemical by aquatic organisms are of environmental concern.

3.1 Internalization by Aquatic Organisms

Micro plastics interact with aquatic organisms through adhesion, absorption, ventilation and ingestion. Over 260 different species have been reported to have taken in plastics, among which 100 are marine species [35,17,36,16]. Species trait, such as habitat preferences and their feeding strategy determines their level of exposure to micro plastics. Suspension feeders; will ingest particles suspended in water, while deposit feeders; forage on particles in sediments, and suction feeders ingest the prey together with surrounding water. Meaning aquatic species can directly consume or accidentally confuse micro plastics with their natural prey, especially if they share the same characteristics such as, color, size, and shape and fouling. Also preying on organism that has consumed plastics can lead to their bio magnification along the food chain [36,37,13,11,34].

3.2 Micro-plastic Additives and Associated Risk on Aquatic Organisms

Additives used to enhance functional and durability properties of plastics (such as; Phthalates, poly-fluorinated chemicals, bisphenol A (BPA), POP, heavy metals, brominated flame retardants and antimony trioxide) are toxic to life. Micro plastics are insidious pollutants, and have been reported to contain 1,000,000 times more of PCBs DDT, PAHs, than the surrounding water. Some of these chemicals such as nonylphenol organic compounds are endocrine disruptors, and can impair the physiological functions of an organism. Also, leaking of these toxins into water, exposures them to aquatic organism and bio-magnification along food chain [10,38,16, 39,36,17,40,41].

3.3 Interaction of Micro-plastics with Microbes

The structure and small sized micro plastics provide high surface to volume ratio, for colonization by microbes. Interaction of micro plastics with microbes affects their sorption and desorption capacity, degradation rate, density and flocculation [14,42,19]. Zettler et al. [35] reported different bacterial taxonomic assemblages associating with micro plastics from those in surrounding waters. He observed that micro plastics facilitate transportation and introduction of non-indigenous (alien) species into new environments, affecting the community structure and composition. Changes in communities structure and composition resulting from these associations are yet to be understood, due to their complexity and redistribution patterns [43,44,4].

3.4 Potential for Human Exposure to Micro Plastics

A human being consumes about 70,000 micro plastic particles annually, from seafood, drinking water, air and salt among others [45]. Contamination of sea salts with micro plastics occurs during or after crystallization from saline waters, packaging materials, or from salt additives such as synthetic folate acids or folic acid [16]. Contamination of seafood with micro plastic is of human health concern. While it has been argued that most fish species are gutted before consumption, there are reports of presences of micro plastics in exceptional small pelagic fish, such as sardines, anchovies, sprats, and crustaceans (e.g. shrimps and lobsters), and echinoderms (e.g. urchins), and seaweeds that are eaten whole, and this exposes humans to micro plastics. In Ireland, over 6500 micro plastics particles/m^3 have been reported in untreated private water supplies, and 1600particles/m^3 in public water supplies. Removing micro plastics in public water supplies includes screening, flocculation, sedimentation/floatation, filtration, disinfection, pH correction and fluoridation, but many suppliers only have disinfection as a treatment. Boiling drinking water can leach toxins from micro plastics into drinking water. With current reports of invasion of micro plastics into human unborn babies, this has risen concerns of possible transference of interacting toxic chemical into unborn babies [17,4,33].

3.5 Prevailing Regulatory Frame Work to Manage Plastic Pollution

There is no specific international convention that fully addresses plastic pollution, but a number of international and regional instruments have indirectly been amended to address the issue. Starting from 1972, there was the London Dumping Convention that aimed at reducing dumping of waste into the Ocean; closely related this convention was the 1973 International Convention, for Prevention of Pollution by garbage from Ships ("MARPOL"). The Conservation of Migratory Species of Wild Animals (referred as "CMS" or the "Bonn Convention") adopted in 1979, targeted to protect migratory species from entanglement by lost fishing gears including fishing net. However, the most comprehensive treaties were, the United Nations Convention on the Law of the Sea (1982 UNCLOS), that included prevention of marine pollution from ships and land-based sources, and The amendments of 1992 Convention on Biological Diversity that categorized micro plastics as hazardous waste. In 1995, The Food and Agriculture organization-(FAO) agreement, on Code of Conduct for Responsible Fisheries, also aimed at preventing harm of marine animals from lost gears, while the amendment of the Basel protocol (1992) include micro plastics and plastics waste as carriers of toxins. The Sustainable Development Goals (SDGs) 4, 6, 12 and 14 by implications have addresses marine plastic pollution in setting implementations targets.

4. CONCLUSION

Regional conventions and agreements that aims at combating plastic pollution include; The Nordic Ministerial Declaration of 2019; the Heads of Government in Caribbean Community (CARICOM) St Johns Declaration, of July 2019, and the 17th session of the African Ministerial Conference on the Environment (AMCEN), of November 2019. The Marine Strategy Framework Directive (2008) that covers the Baltic sea; the North-east Atlantic Ocean, Mediterranean Sea and Black Sea, and the new European Union (EU) Circular Economy Action Plan of March 2020, The Group of 7 (G7) and Group of 20 (G20) have also addressed the issue of marine plastic pollution, at their action plans. The European directive on Drinking Water (98/83/EC) on protecting drinking water from all potential sources, have included micro-plastics.

Currently over 60 countries have introduced policies to curb plastic pollution globally, many being in Africa. In East Africa Community, the six members already have national policies to mitigate plastic pollution. Rwanda, was the first to ban the manufacture, use, sale and importation of all plastic bags, but Kenyan law went further by incriminating the sale or use of single-use plastics with the highest penalties.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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