



## Review

# Particulate plastics in drinking water and potential human health effects: Current knowledge for management of freshwater plastic materials in Africa<sup>☆</sup>

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## ABSTRACT

Plastic materials have contributed to the release of environmentally relevant particulate plastics which can be found almost everywhere and may be present in drinking water. Human exposure to these materials is diverse and our understanding of their internalization in the human body is incipient. This review discusses the state of knowledge of particulate plastics exposure in drinking water and the potential risks of adverse health in the human body. Particulate plastics have problematized water systems worldwide, and about 4,000,000 fine plastics may be ingested from drinking water annually by an individual. Testing methods for these materials in environmental media are presently inconsistent and standard protocols do not exist. Their potential ecotoxicological consequences are recognised to be linked to their physicochemical diversity, biological transpositions, and cytological tolerance in living organisms. It is observed that toxicological endpoints are varied and lack properly defined modes of action. In particular, fine particulate plastics have been observed to translocate into body tissues and cells where they are capable of provoking endocrine disruption, genetic mutations, and cancer responses. We propose a reclassification of particulate plastics to cater for their biological deposition and attributable risks of adverse health. Environmental management of particulate plastics in many developing countries is weak and their potential releases into drinking water have received limited research. Given that large populations are exposed to fresh surface water and plastic packaged drinking water worldwide, and that the risk assessment pathways are unvalidated at the moment, we argue for developing countries to increase their capacity for the environmental monitoring and circular management of plastic materials. Large-scale epidemiological cohort studies and surrogate assessment pathways are also recommended to provide a better understanding of the hazard characterization of particulate plastics exposure.

## 1. Introduction

Plastic waste generation and mismanagement have dire consequences for human health and environmental sustainability. In many developing countries, waste rejection, and environmental emissions have resulted in the accumulation of plastic materials in water systems resulting in pollution of the water and adjoining ecosystems. The adoption of plastic materials such as polyethylene terephthalate (PET) and low/high-density polyethylene (L/HDPE) for food and water packaging in sub-Saharan Africa (SSA) has contributed to large volumes of discarded plastics in the region (Keough and Youngstedt, 2018). This

has become a serious threat to aquatic life, drinking water management, and public health security in general. Plastic waste accumulation and mismanagement of land, water, and air continue to pose developmental challenges for the provisioning of good drinking water for populations globally. The importance of drinking water is manifested in the amount of water in a fat-free body mass (Jequier and Constant, 2010). Ingestion exposure is the major pathway for many substances that enter the human body. In many regions around the world, plastic packaged water is the drinking water of choice for large populations (Angnunavuri et al., 2022b; Chakraborty et al., 2022; Mbala-Kingebeni et al., 2021; Stoler, 2017; Udoh et al., 2021). Packaged water is generally sourced from

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surface water, underground well/borehole water, and municipal supplies, while the package may be virgin or recycled. Freshwater systems, including groundwater wells, rivers and streams, remain significant sources of potable water for the vast majority of rural communities in Africa.

The ultimate target for sustainable development goal (SDG) 6.1 is the universal supply of safely managed and affordable drinking water by all and for all by 2030 (United Nations, 2020). Presently, only about 30% of the population in sub-Saharan Africa (SSA) drink from safe and improved water resources. On a regional basis, SSA continues to lag as shown in Fig. 1 and it will take significant and ambitious efforts to meet the SDG target. It is therefore important that issues of safe water management are prioritized to protect public health and the general well-being of people in this area.

Although plastic materials are environmentally persistent, they are not stable and may undergo degradation, fragmentation, diminution, depolymerization, and demineralization (Abbasi et al., 2019; Arias-Andres et al., 2018; Bouwmeester et al., 2015; Filella, 2015; Gallo et al., 2018; Gomiero et al., 2019; Hu et al., 2019; Markic et al., 2018; Rist and Hartmann, 2018). Various factors, including chemical, microbial, mechanical, and ultraviolet rays from the sun weaken the plastic material and eventually break its structural integrity. Consumer and non-consumer waste plastics breakdown into macro, then meso, micro and nano-sized particles which can alter the hydrogeochemistry as well as the microbiology of many water bodies (Fahrenfeld et al., 2019; Horton, 2017; Koelmans et al., 2019; Lambert and Wagner, 2016; Piao et al., 2019; Triebkorn et al., 2019). In the present study, the term particulate plastics will be used to broadly refer to all environmentally and biologically relevant plastic particulates including microplastics, nanoplastics and sub-nanoplastics. In specific cases, fine particulate plastics will be used to describe only nano and subnanoplastic particles. Generally, plastics are invasive materials with an indefinite life span, that once produced require centuries or millennia to disintegrate, and particulate plastics may enter the global food chain. Plastic materials in contact with water may introduce these minute plastic materials into the water which can then be ingested and may cause potential adverse health effects. Water treatment plants continue to face technological deficiencies in achieving 100% removal of particulate plastics in raw water systems (Ding et al., 2020; Enfrin et al., 2019; Kirstein et al., 2020; Pivokonsky et al., 2018; Wang et al., 2020b).

In many developing countries, rural communities drink water directly from freshwater systems without any depuration. On the other hand, municipal water supply systems rely on treatment programs such as filtration, ionization/deionization, and chemical/biological

disinfection to process freshwater and deliver safe potable water to populations. Water treatment plants all over the world have been challenged by the presence of particulate plastics in raw water, and the removal of particulate plastics in wastewater. An exploratory study conducted by Mintenig et al. (2019) confirmed the presence of particulate plastics in advanced water treatment systems with indications that the particles could originate from abrasive weathering of plastic materials used in water purification. Plastic particles have also been sampled from borehole and well drinking water (Mu et al., 2022; Oni and Sanni, 2022). Due to the inevitability of particulate plastics exposure in drinking water and their uncertainties in human health risk characterization, the scientific community continues to advance research that will improve our understanding of particulate plastics exposure. Particulate plastics are identified as an emerging environmental contaminant that will impact the integrity of global water resources but to what extent this, and the resulting impact on human and environmental health will be, is still being determined. What is certain is that global, regional and national initiatives must interplay to drastically reduce their release and trophic accumulation. The subsequent narratives highlight the production and management of plastics and the impacts of particulate plastics on the environment and human health with a focus on Africa.

## 2. Plastic waste mismanagement

### 2.1. Plastics production and applications

Plastics are versatile synthetic and semi-synthetic products with multifarious applications (Horton and Dixon, 2018; Mintenig et al., 2017) due to their lightweight, malleability, durability and low cost (Prata et al., 2019a), although some reinforced dense plastics are used in marine applications (Cheremisinoff, 1997; Murphy, 1994; Thompson et al., 2009). The preferred input materials for conventional plastics manufacturing are petroleum and natural gas (Suchak and Irving, 2018). Renewable resources such as sugar, corn, and cassava have been used recently for the manufacture of biodegradable plastic materials (Bowmer and Kershaw, 2010; Palm and Svensson Myrin, 2018). Ultra-violet (UV) stabilizers, flame retardants, antioxidants, plasticizers, lubricants, rheology modifiers, heavy metals, intermediate products, and other chemicals may be added to confer specific properties to the plastic polymer (Espinosa et al., 2016; Nar, 2019). Global annual throughput continues to rise, estimated at 450 million tons in 2020 (Mafuta et al., 2021). In terms of production, Asia and the Pacific regions lead the pack (50%), followed by the North America Free Trade Area (NAFTA) (19%), and Europe (19%) (Barra et al., 2018; Geyer et al.,

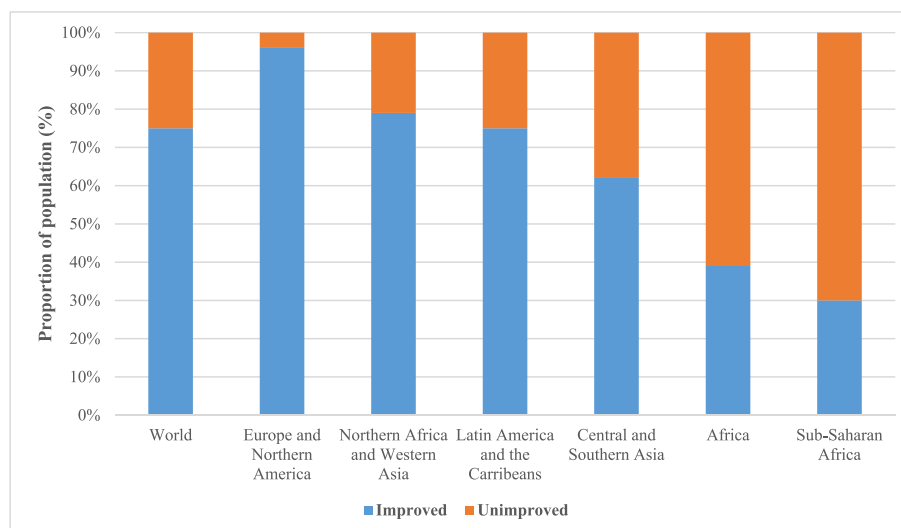


Fig. 1. Global snapshot of the progress towards achieving SDG 6.1 (UNICEF, 2022; United Nations, 2022).

2017; Serranti and Bonifazi, 2019; Woldemar, 2019). The Middle East and the Africa Continental Free-Trade Area (AfCFTA) altogether are estimated to produce some 7% (Geyer, 2020; World Wide Fund for Nature, 2022).

Apart from some plastic pellets that are not stabilized, most plastic materials are generally thermally stable, chemically inert and resistant to ultraviolet (UV) radiations (Espinosa et al., 2016), making them the material of choice for a wide range of applications such as packaging, building and construction, communication, industrial machinery, entertainment, sports, transportation, furnishing, apparel, and agriculture. They are an important part of medical devices, they offer safe food packaging, and deliver water (including potable and agricultural water) as well as offer sewerage services to billions of people around the world. As of 2016, the industries with the highest uptake of plastic products, and the estimated industrial releases are shown in Fig. 2.

### 2.2. Plastic waste generation and management in Africa

Worldwide, research into the production of biodegradable plastics is still a novelty, leading to the dumping and landfilling of mostly synthetic non-biodegradable plastic wastes. Between 2016 and 2050, an estimated 12 billion metric tons of waste plastics are expected to be land-filled or emitted into the natural environment and more than 5 trillion particulate plastics in the oceans (Barra et al., 2018; Cox et al., 2019), since only a small proportion of the annual production outlay is recirculated. It has been estimated that the number of plastic materials in the oceans will outstrip that of fish by 2050 without the widespread uptake of circular engineering linkages (Barra et al., 2018; Hasselerharm, 2020). Waste plastics are a pervasive and persistent global challenge with negative impacts on the environment, national and regional economies, human welfare, and landscape aesthetics.

Plastic wastes generation and management have been a challenge for developing nations in Africa to cost-effectively and efficiently manage (Filho et al., 2019; Thompson et al., 2009; Zalasiewicz et al., 2019). Globally, plastic wastes have been deemed to account for about 20% of municipal solid wastes (Barnes et al., 2009; Crawford and Quinn, 2017; Eberé and Ngozi, 2019; Rocha-Santos and Duarte, 2019). The proportion of plastic litter in urban waste has been a source of concern for economic development and environmental sustainability in Africa. Data on plastics production is scarce but Africa is home to large quantities of dumped plastic wastes and plastic litter, with the propensity to infiltrate the different types of drinking water resources. In most parts of Africa, waste collection, treatment and disposal systems are inadequate leading to 80% of leakages of waste plastics into oceans, rivers, and land

(Abdellatif et al., 2021; Babayemi et al., 2019; Okeke et al., 2022). On an economic upside, these dumps or landfills offer recycling value-chain opportunities to scavengers to earn income by picking plastics which would otherwise have been burnt in the open. The inequalities in uncontrolled plastic waste disposal globally are reflected in Fig. 3.

Until recently, large volumes of plastic waste were diverted from landfills in developing countries and exported to China and other countries with advanced and large-scale recycling/recovery capabilities. The decision by the Government of China to ban plastic importation from 2018 has not only posed a serious challenge to a worldwide recirculation of plastics but also imposed responsibility on plastic exporting nations and developing countries to explore domestic solutions for the treatment of waste plastics (Global Alliance for Incinerator Alternatives, 2019; Wang et al., 2020a; Wen et al., 2021). Other countries, namely Malaysia, Taiwan, Thailand, Vietnam, and India, have also imposed similar bans and restrictions on the importation of plastic scrap as they attempt to protect their environments. The African continent boasts of the largest number of country-level regulations for single-use plastics than any other continent (United Nations Environmental Programme, 2018), but the lack of verifiable data on plastic materials in the continent may imply that Africa consumes and leaks more plastics than presently reported.

Lebreton and Andrady (2019) have pointed to increasing production and accumulation of plastic products and plastic wastes in the future on the African continent due to an increasing population, inadequate local manufacturing and recycling capacity, and lax environmental conservation mechanisms (Abdellatif et al., 2021; Mavropoulos, 2019). A further incentive for plastic waste generation is the expected boom in intra-continental trade as a result of the AfCFTA agreement (Bengoa et al., 2022). Local production has been persistently lower than demand, making the continent a net importer of plastics and plastic raw materials (Babayemi et al., 2019). Between 1990 and 2017, it has been estimated that total imports of plastics amounted to about 172 metric tons in 33 African countries, the figure expected to double by 2030 (Akan et al., 2021; Babayemi et al., 2019). On a regional level, imports into the continent are largely dominated by North Africa, with sparse contributions from West Africa and South Africa (Babayemi et al., 2019). The World Health Organization (WHO) has advocated for improving recycling programmes, reducing littering, improving circular solutions, reducing the use of plastics, and decreasing waste inputs into the environment by industries as part of broader measures to reduce plastics pollution (Marsden et al., 2019).

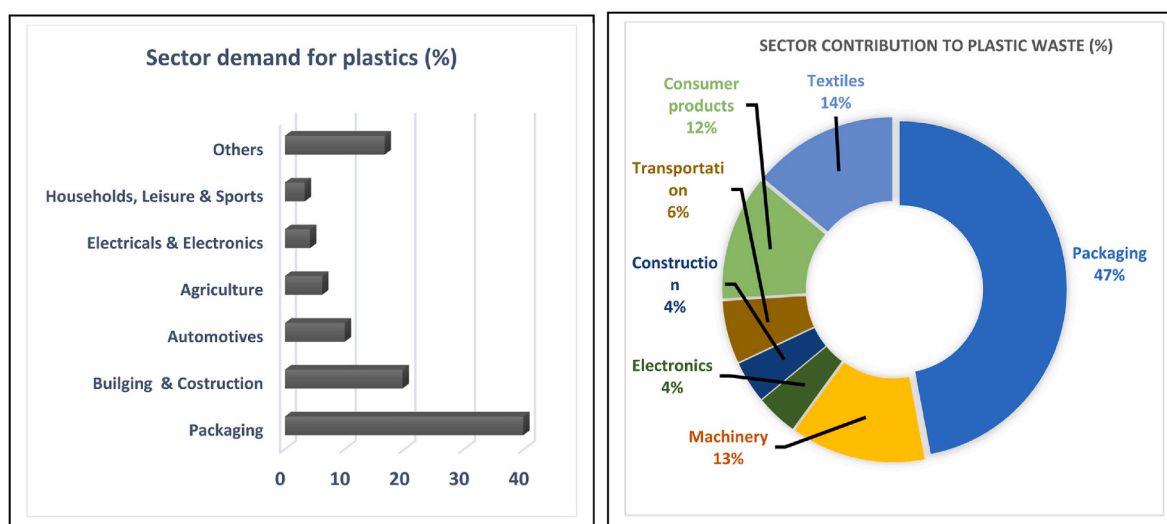


Fig. 2. Global Plastic demand and waste generation in 2016 (Geyer et al., 2017; Serranti and Bonifazi, 2019).

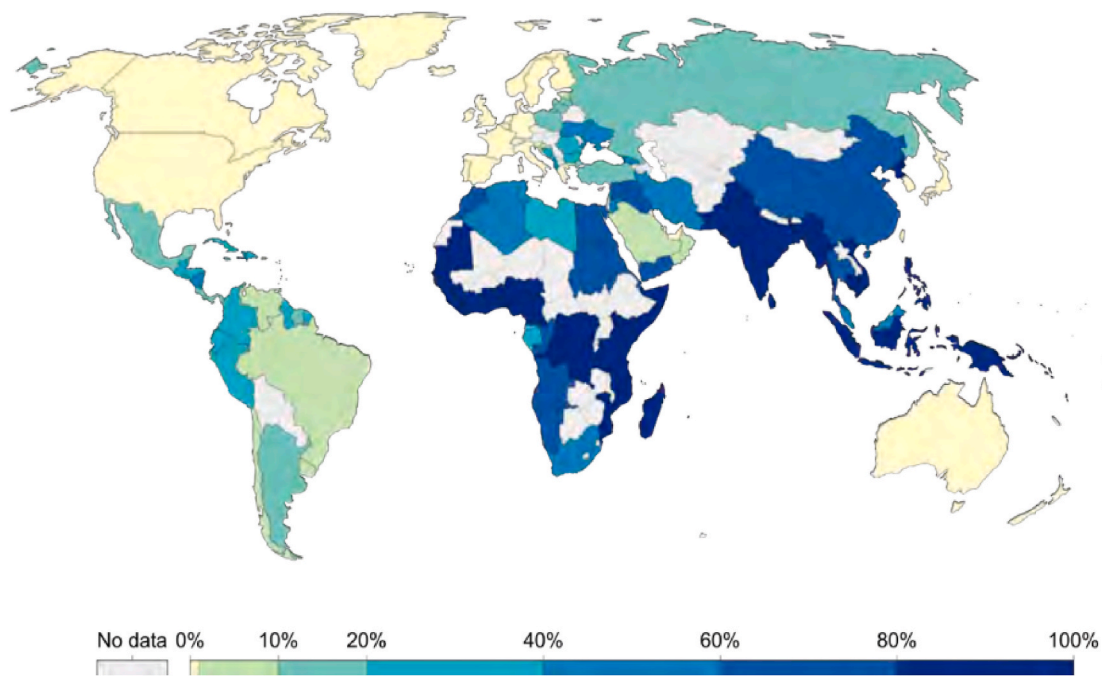


Fig. 3. Uncontrolled plastic waste disposal from a global perspective as of 2019 (Santander, 2021).

### 3. Externalities of environmental particulate plastics emissions

Across the globe, the proliferation of plastic wastes is widespread and a major contaminant of aquatic and terrestrial ecosystems. Weak governance systems, litter-inducing social behaviours, lack of awareness, population density, urbanization, and scarce hydrological information about the consequences of plastics pollution have been associated with the exponential surge of waste plastics in many developing countries. Plastics will continue to play a central role in the world and society, but the utilization and mismanagement of waste plastics are likely to pose existential threats to ecosystems and their services due in large part to plastic particulates (Barnes et al., 2009; Baztan et al., 2018; McKinney, 2019; Thompson et al., 2009). Barra et al. (2018) have posited that the current linear models of producing plastic materials are a principal driver for natural resource depletion, waste plastics accumulation, environmental degradation, climate change, and human health impairment. Verster et al. (2017) have indicated that the risks of particulate plastics may be more pronounced in developing countries where large populations depend on land and water resources for daily sustenance and general economic wellbeing.

Plastic wastes in general, and particulate plastics, in particular, are easily transported over long distances and become ubiquitous in their distribution on land, water and air (Barnes et al., 2009; Horton and Dixon, 2018; Mason et al., 2016; Shim et al., 2017; United Nations Environmental Programme, 2018; Vince and Hardesty, 2018). Land is the primary host for most particulate plastics which are then moved into aerial and aquatic systems. Migwi (2021) estimated that microplastics contamination of Naivasha lake in Kenya was nearly 3 orders of magnitude lower than the surrounding sediments of the lake. Waterborne particulate plastics are pervasive in anthropized locations, with weak governance systems accounting for their abundance. Particulate plastics are very buoyant and their distribution in air is modulated by atmospheric processes (Alfonso et al., 2021; Liu et al., 2019; Wright et al., 2020). Microplastics have been detected in remote locations (Allen et al., 2019; Zhang et al., 2019) and in glacial ice (Kanhai et al., 2020; Kelly et al., 2020; Peeken et al., 2018). Hitherto pristine environments such as the French Pyrenees (Allen et al., 2019), the Antarctic sea ice (Kelly et al., 2020), the Arctic Central Basin (Kanhai et al., 2020; Peeken et al., 2018) and the Alps (Bergmann et al., 2019) have been

compromised by particulate plastics. The sources, fate and transport of these particulate plastics have been comprehensively reviewed (Angrunavuri et al., 2020; Pereo et al., 2020; Siegfried et al., 2017).

Ingestion of microplastics by freshwater fauna can lead to physical blockage, internal energy depletion, inhibited growth, fertility impacts, starvation, and even death. Ecological toxicity consigned to notable additives and sorbed chemicals such as phthalates, polybrominated diphenyl ethers (PBDEs), persistent organic pollutants (POPs), polycyclic aromatic hydrocarbons (PAHs) and halogenated flame retardants (HFRs) have been well documented (Anbumani and Kakkar, 2018; Avio et al., 2017; Blackburn and Green, 2022; Cao et al., 2022; de Souza Machado et al., 2018). Plastic microfibers, filaments, and granules provide avenues for the transfer of different microbial species across the world, leading to the creation of foreign species in the ecologies of affected regions (Shen et al., 2019b). The diversity in particle sizes and dimensions will play significant roles in hazard characterization (Kooi et al., 2021). As a first step towards global appreciation of the plastics problem, Rochman et al. (2013) have argued for the classification of plastics as hazardous environmental materials to provide an imperative for their management. The impacts of particulate plastics on biota are summarized by Science Advice for Policy by European Academies (SAPEA) (Science Advice for Policy by European Academies, 2017) as shown in Fig. 4.

Scientists working with the International Union for the Conservation of Nature have found plastic and plastic particle materials in endangered and vulnerable fauna such as the Hawaiian monkey, sea turtle, and fur seal (Rochman et al., 2016). A wide range of aquatic organisms – including zooplankton, invertebrates, fishes, seabirds, and whales – are exposed to particulate plastics through direct ingestion of water and indirectly as predators in food webs. Reports compiled by the United Nations Environmental Programme (UNEP) suggest that more than 1million birds and over 100,000 marine animals die each year as a result of plastics ingestion (Turpie et al., 2019; United Nations Environmental Programme, 2018). Land-based plastics have been determined to negatively influence aesthetics, food production, and air quality. Plastic pollutants have been a major part of flood metrics in most developing countries as they easily accumulate in drainage systems and block watercourses.

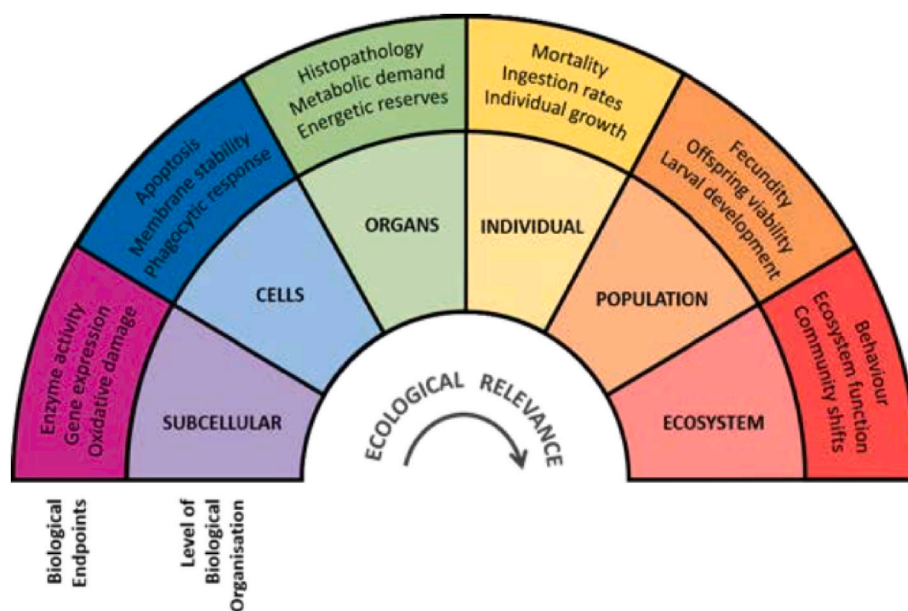


Fig. 4. Impacts of particulate plastics on different levels of biological organizations (European Commission, 2019; Science Advice for Policy by European Academies, 2017).

#### 4. Particulate plastics in fresh and drinking water

Drinking water broadly refers to safe potable water systems and include groundwater, surface water, and tap/delivered water. Freshwater constitutes only 0.014% (about 200,000 cubic kilometres) of global water reserves on earth (King and Brown, 2021). The quantity and quality of this limited resource is essential for the existence of the many lifeforms on earth and human development. The challenge however is the capacity to meet the development needs of an ever expanding human population while preventing freshwater pollution/degradation, over-exploitation and habitat/biodiversity losses. Freshwater has been an important asset for drinking water management, sanitation and hygiene, recreation, climate change mitigation through carbon sequestration, food and energy security, spirituality, warfare, flooding, and the outbreak of disease in man and animals.

Significant loadings of plastic materials and particulate plastics have been found in some of the world's freshwater bodies due to wind or surface run-off (Bauerlein et al., 2022; Hamid et al., 2018; Horton and Dixon, 2018; Koelmans et al., 2019; Pivokonsky et al., 2018; Wagner et al., 2018). A critical review of microplastics contamination of fresh and drinking water resources ranks polyethylene, most commonly used for packaging, as the most abundant material in these systems (Koelmans et al., 2019). The study also found a predominance of fragmented and fibrous particles, attributable to anthropogenic activities in surface water systems. Equivalent number of particulate plastics have been identified by Mason et al. (2018) and Piao et al. (2019) on wastewater effluents and fresh water, instigating the need to increase scientific investigations on microplastics in freshwater and drinking water resources. Field studies by Egessa et al. (2020), Weideman et al. (2019) and Biginagwa et al. (2016) have pointed to large scale urban influences in the distribution of microplastics in the Orange-Vaal river systems and Lake Victoria, compared to remote locations, and called for proper waste management mechanisms to safeguard these water courses from anthropogenic pollution. Lake Victoria is a major tropical freshwater body that is home to significant drinking water headworks in Kenya, Burundi, Tanzania, Rwanda and Uganda. Recently, both lake Victoria and the Orange-Vaal river system have been determined to be contaminated with hazardous chemicals of plastic origin (Chirikona et al., 2015; Egessa et al., 2020; Onchiri et al., 2021).

Global studies conducted in 18 countries across Africa (Uganda),

Europe (Germany, England, Slovakia, Switzerland, France, Ireland, Italy), South America (Brazil, Ecuador, Cuba), North America (USA, Mexico), Asia (China, India, Indonesia, Thailand), and the Middle East (Lebanon) by Mason et al. (2018) and Kosuth et al. (2018) detected diverse fine particulate plastics in bottle water, tap water and beer. The degradation of plastic materials containing drinking water has also been signalled as another source of particulate plastics in drinking water (Huang et al., 2022b; Winkler et al., 2022). A recent study in Asia by Tong et al. (2020) found 440 particles $L^{-1}$  in tap water systems, mostly mini-micro grade and preponderated by polyethylene and polypropylene materials. Using conventional water treatment plants, Pivokonsky et al. (2018) also found microplastics in raw and treated water, inferring that these particles have the propensity to evade filtration systems and enter domestic water supply systems. A study conducted by the University of Newcastle concluded that the average person consumes 1972 particulate plastics every week from food and beverages, and 1769 particles (or 88%) from drinking water alone (World Wide Fund for Nature, 2019). Further quantitative exposure analysis of published literature in the European Union estimated an annual intake of 3,569,000 particulate plastics per person per year from bottle water (Danopoulos et al., 2020). Bottle aging, mechanical stress and exposure to ultra violet rays from the sun have been shown to significantly influence the degradation of PET materials containing drinking water (Taheri et al., 2023). Apart from the physical particles, plastic consumer packaging has been observed to introduce novel contaminants such as phthalates and bisphenol-A into drinking water and food (Angrunavuri et al., 2022a; Asigri, 2018; Baranenko et al., 2021; Edwards et al., 2022; Garcia-Fabila et al., 2020; Razali et al., 2021; Wang et al., 2021; Zaater et al., 2014). The infiltration of potentially toxic novel contaminants in drinking water supplies due to the presence of particulate plastics may go undetected. In the West African region, Wardrop et al. (2017) reported 28,000 tons of waste water plastic materials per year given the large scale environmental emissions within the region. The few freshwater bioassay studies in Africa reveal the contamination of aquatic specimen with particulate plastics (Akindele et al., 2019; Jeevanandam et al., 2022), and the prevalence of microplastics in the surrounding water (Dahms et al., 2020; Faulstich et al., 2022; Shabaka et al., 2022).

Many developing nations lack advanced drinking water treatment systems that can eliminate particulate plastics during water treatment. Water treatment plants have acted as sources of contamination as well as

controls for particulate plastics during water treatment. Micro/granular filtration techniques such as ultrafiltration, nanofiltration, micro-filtration, reverse osmosis, and membrane bioreactors offer promising removal rates for particulate plastics than traditional filtration systems (Barbier et al., 2022; Im et al., 2021; Oh et al., 2019; Wang et al., 2022; Wang et al., 2020b). A systematic review of existing literature by Barchiesi et al. (2021) has suggested that combined systems involving coagulation, flocculation, sedimentation, sand/activated carbon filtration and floatation were more effective than stand-alone systems and could remove up to 88% of source water particulate plastics (Minténig et al., 2019; Pivokonsky et al., 2018; Wang et al., 2020b). These removal efficiencies were based on predetermined quotients of the number of recovery particles in control samples. By spiking the samples, Lares et al. (2019) was able to achieve 93% recovery for wastewater and sludge samples. Testing capabilities that can adequately detect particulate plastics for routine monitoring, and the regulatory regimes for mitigating plastic and particle pollution are presently inadequate.

The ubiquitous nature of plastic particle pollution means that their potential impacts will not be limited to host environmental compartments, but the biological consequences of intake may play an overriding influence in toxigenic assessment. Plastic microparticles are present and will be a persistent, environmental danger around the world, requiring strategic research and engineering methodologies to identify and mitigate major sources of pollution and understand pathways for deposition and accumulation in biological matrices. Very few studies on the subject of particulate plastics in packaged drinking water have been conducted in developing countries around the world. Studies that integrate large scale environmental samples to understand the transport of particulate plastics and their source apportionment in drinking water may contribute significantly to new designs for drinking water treatment.

## 5. Potential human health risks to particulate plastics - perceived or real

Scientific reports continue to inventory the trophic fugacity of micro and nano particulate plastics and examine their toxicological modes of action. However, their biological effect-actions through ingestion intake in drinking water are still incipient and inconclusive. Could particulate plastics originating from drinking water provoke pernicious responses in human? Quantitative and qualitative studies have identified and enumerated varying concentrations of particulate plastics in fresh surface waters, tap water and packaged water (Ali, 2019; Di et al., 2019; Ding et al., 2020; Kirstein et al., 2020; Lee et al., 2021; Minténig et al., 2019; Paredes et al., 2019; Pivokonsky et al., 2018; Schymanski et al., 2018; Shen et al., 2020; Shruti et al., 2020; Wang et al., 2020b), but their relationship with adverse human health has only been theorized. The World Health Organization has indicated that data inconsistencies in current literature, and the lack of standardization in testing methodologies and data reporting, do not lend credence to any real hazard due to particulate plastics in drinking water. The report by Marsden et al. (2019) rather proposes for continued source water protection to prevent the potential presence of particulate plastics and other contaminants of concern in drinking water.

Human exposure to particulate plastics may occur through ingestion, dermal uptake, and inhalation (Revel et al., 2018). Following exposure, and as exogenous materials, fine particulate plastics may trigger an inflammatory response, as they resemble foreign bodies which immune cells try to eliminate. The shear proportion of drinking water content in the human body (Jequier and Constant, 2010) suggests that drinking water may contribute to significant loading of particulate plastics in the human body. High exposure frequencies through drinking even at low doses will bioaccumulate in the body, and can lead to unspecified and unconsidered human existential threats due to their persistence. More significantly however, present human risk assessments that characterise mechanistic trajectories and pharmacokinetic indications do not provide adequate reliability and minimum recommended thresholds for the

complex and heterogeneous matrices like sub-micro and nano congeners (Gouin et al., 2022). Despite these uncertainties, the State of California has listed particulate plastics in drinking water as part of its health and safety code to provide for their testing, reporting, interpretation, and public disclosures (California State Water Board, 2020).

### 5.1. Physical and chemical properties of biological and health importance

Size, surface chemistry, and surface topography/curvature have been noted for the behaviour and toxicity of particulate plastics (Bakand et al., 2012; de Souza Machado et al., 2018; Shen et al., 2019a; Stapleton, 2019). Studies have suggested that the egestion of regular microplastics is more likely than irregularly shaped microplastics (Šilhánková, 2018). On a surface to mass basis, irregular particles possess higher surface to volume ratio than regular particles which may enhance their biochemical and physical interactions in living cells. Popat (2016) has argued that due to the higher surface area to volume ratio and stronger electrostatic properties, smaller particles tend to elicit bigger chemical and physical impacts on biological systems and the environment. Recent developments also point to the fact that the hydrophilic potential of particulate plastics may be more useful in particle removal than surface charge ratio (Enfrin et al., 2021a; Enfrin et al., 2021b; Maliwan et al., 2021). These physicochemical properties will be important in determining the fate and transport of particulate plastics in drinking water and in the human body.

Environmental plastics may alter the geochemistry of their hosts due to their chemical composition and long-range transport behaviour. Particulate plastics may sequester organic and inorganic chemicals, and transport many other toxic materials in their hosts (Ma et al., 2019; Mohamed Nor, 2022; Oßmann et al., 2018; Prata et al., 2019b; Rocha-Santos and Duarte, 2019). Particulate plastics tend to exhibit low water solubility and high octanol-water partitioning coefficients ( $\log K_{ow}$ ), giving them high proclivity for fatty tissue deposition (Keresztes et al., 2013) and affinity for lipophilic substances (Shan et al., 2020). Plastic nanoparticles may also alter the biogeochemistry of living cells that may affect biochemical pathways. A molten plastic slurry in a closed system is a complex soup of heavy metals, various pesticides, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, fluoroalkyl substances and endocrine disrupting chemicals among others. There is evidence that polymerization reactions during plastics production do not go to completion, leading to aging depolymerization of chemicals such as 1,3-butadiene, ethylene oxide, antimony trioxide, and vinyl chloride (Avio et al., 2017; Clunies-Ross, 2019; Halden, 2010; Klein, 2011; Strong, 2006). Plastic components including plasticizers, colorants, lubricants, foaming agents and flame retardants may also leach out in solution or weather away under light stress (Hureiki and Mouneimne, 2012; Marsden et al., 2019; Tukur et al., 2012). The toxins discharged by plastic materials and particulate plastics can be ingested and absorbed by humans resulting in systemic toxicity and genetic modifications especially in the infant and the unborn (Manikkam et al., 2013; Tourinho et al., 2019).

Endocrine disrupting chemicals (EDCs) include organic and heavy metal compounds that are known to cause genetic mutations, cancer, and reproductive impairments. They include a wide range of industrial chemicals such as benzotriazole UV stabilizers, bisphenol-A, haloalkyl substances, dioxins, flame retardants, phthalates, antimony, lead and cadmium which are used as ingredients in plastic materials (Chakraborty et al., 2022). EDCs have been isolated from Chinese, Japanese and German water systems and observed to show strong estrogenic and endocrine disruption activity in vertebrates and invertebrates, and long-range transport behaviour (Benjamin et al., 2017; Espinosa et al., 2016; Manikkam et al., 2013). EDCs have also been shown to leach out from plastic materials, and either jointly or severally, may be associated with impaired fertility, delayed neurodevelopment in children, immune disorders, metabolic disorders, and hormonal cancers. Antimony trioxide ( $Sb_2O_3$ ) (ATO), an EDC suspected to cause human cancer

(Sundar and Chakravarty, 2010), is often added as an essential polycondensation catalyst during the manufacture of PET materials (Duh, 2002; National Research Council, 2000; United States Environmental Protection Agency, 2014; Westerhoff et al., 2008). A study conducted by Mortula and Ahmad (2013) detected significant quantities of antimony in PET bottle water in the United Arab Emirates, and associated the concentrations with incubation temperature and time. Other metals and their congeners of plastic origin such as arsenic, aluminium, barium, chromium, mercury, cadmium, titanium, tin, lead, bromium, and cobalt have been identified in drinking water samples and may be linked with various medical conditions that could affect human life (Okeke et al., 2022).

### 5.2. Effects of plastisphere

Due to their surface properties, particulate plastics can transport microorganisms that may change the microbial ecology of biosystems. This plastisphere may include a novel community of microbes, including harmful types, which can trigger various disease conditions, and gene transfers (Shen et al., 2019b; United Nations Environmental Programme, 2016). Fine particulate plastics may modulate immune responses in healthy individuals by interfering with their natural bioflora. The ability of particulate plastics to carry microorganisms may make them the vector for pathogenic species and antibiotic-resistant bacteria (Blackburn and Green, 2022). Toxicological hazards relating to inflammation and oxidative stress have been shown to be more pervasive in ecotoxicological studies (Coffin et al., 2022a), and some association between particulate plastics and impaired immunity has been suggested (Tagorti and Kaya, 2022). Zhang et al. (2022) investigated the relationship between particulate plastics and Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) pseudovirus using *in vitro* studies and observed an enhanced binding of the virus with the particles, and increased infectivity of human cells. Such developments will be useful in understanding the emergence, characterization and management of novel disease conditions such as Coronavirus Disease-2019 (COVID-19).

### 5.3. Evidence of particulate plastics in the human body and health implications

Quantitative and qualitative causality from *in vitro* studies, model animal bioassays and human post-mortem investigations have provided some insights into the hazards that fine particulate plastics may induce in biological systems. Nano and subnano-plastics are small enough to penetrate deep into organs and cells with unknown consequences (Brun et al., 2014; EFSA, 2016; European Commission's Scientific Advice Mechanism, 2018). Research is still ongoing to account for the total biological diversity of particulate plastics in the human body (Danopoulos et al., 2022; Leslie et al., 2022; Yee et al., 2021; Yuan et al., 2022), but their presence in human breast milk (Ragusa et al., 2022) may pose far reaching consequences for the growth and development of breast-fed infants than presently known. The various pathways for biological uptake and the potential health effects of fine particulate plastics, ranging from physical obstruction in body channels to their internalization and participation in biochemical or molecular processes have been detailed by Koelmans et al. (2022). Pathways that illustrate distinct adverse outcomes have been investigated by Thornton Hampton et al. (2022) and observed not to be clearly defined.

Once particulate plastics are translocated into body organs, especially the gut system, paracellular persorption and endocytosis may occur (California State Water Board, 2020; Liu et al., 2021a). Paul et al. (2022) have estimated the cellular uptake of fine particulate plastics using modelled human intestinal and liver cells and observed increasing uptake with decreasing particle size, with broad implications for intracellular homeostasis and membrane toxicity. They also observed localized deposition of particles in the cells, with distinct differentiation for

hydrophilic particles in the cytoplasm and hydrophobic particles intercalating within the lipid layer of the cell membrane. The mechanisms of transport through formalised active and passive pathways, are still unclear. Xu et al. (2019b) mentioned phagocytosis, micropinocytosis, and endocytosis as possible pathways for the uptake of fine particulate plastics by human cells.

Intracellular uptake of nanoplastics results in direct interaction of these particles with organelles, and genetic material with the potential for changes in gene expression, inflammation, and altered biochemical responses. Nano and sub-nanoplastics, which can possess both negative and positive charges, are readily absorbed and may accumulate in the brain, kidney, heart, and liver with potential adverse repercussions for the proper functioning of the central nervous system and reproductive system (Bakand et al., 2012; Enyoh et al., 2019; Pinto da Costa et al., 2019; Waring et al., 2018). Pauly et al. (1998) confirmed the lodging of microplastic fibers in human lung tissue, suggesting that fine particulate plastics may play a role in the aetiology and prognosis of lung cancer. Studies by Khaliq et al. (2011) suggest that plastic dust was more likely to evoke pulmonary dysfunction in plastic factory workers than in unexposed persons. Qin et al. (2022) have observed that chlorinated polystyrene particles were responsible for marked cytotoxic responses in human gastric epithelial cells GES-1. If these observations are validated in upscaled experiments, then current drinking water treatment technologies that employ chlorination for disinfection may require reengineering.

Laboratory studies using fine polystyrene particulate plastics determined the internalization of these particles in human foreskin HS27 cells leading to DNA damage and formation of micronuclei and nuclear buds (Poma et al., 2019). The tendency for fine particulate plastics to aggregate or agglomerate in cells (Gopinath et al., 2021; Xu et al., 2019a), unlike conventionally engineered nanomaterials (EFSA Scientific Committee, 2021), may modulate gene expression, genotoxicity, cellular inflammation and incidences of stroke. Particulate plastics presently do not fulfil standard dispersion protocols for nanomaterials and this technical gap may impair the validity of risk assessment results. Evidence about the presence of particulate plastics in the human body are specified in Table 1. The data shows the recency of the works and the diversity in data reporting.

Cellular fine particulate plastics (cytoplastics) may leach out toxic heavy metals and organic polymeric chemical contaminants that can be detrimental to host tissues and cells (Andrady, 2011; Brennecke et al., 2016; Koelmans et al., 2014; Koelmans et al., 2013; Lu et al., 2018; Polidoro et al., 2022; Sedlak et al., 2017). Alimentary properties such as sorptive capacities of the gut, digestion efficiency, and local chemical gradients will modulate the exchange of chemicals between entrained particulate plastics in food and water and cellular systems in the body. The proposition of a passive sampling theory by Koelmans et al. (2022) may instigate discussions on particle-mediated malnutrition in individuals that are exposed to high levels of particulate plastics. In animal models, *in vitro* studies have confirmed biochemical dysfunctions in iron uptake in chicken exposed to microplastics (Waring et al., 2018).

**Table 1**  
Evidence of particulate plastics in human.

No.	Human Specimen	Maximum Concentration or particle size	Reference
1	Blood	7.1 µg/mL	Leslie et al. (2022)
2	Lungs	3.96 particles/g	Jenner et al. (2022)
3	Breast milk	2.75 g/mL	Ragusa et al. (2022)
4	Cirrhotic liver	3.4 particles/g	Horvatits et al. (2022)
5	Broncho-alveolar lavage fluid	9.18 particles/100 mL	Baeza-Martinez et al. (2022)
6	Sputum	567 particles/10 mL	Huang et al. (2022a)
7	Placenta	~10 µm	Ragusa et al. (2021)
8	Feces	10.19 µg/g feces	Wibowo et al. (2021)
9	Feces	41.8 particles/g feces	Yan et al. (2021)
10	Infant feces	82,000 ng/g feces	Zhang et al. (2021)

Polystyrene particles have shown metabolic adaptations that mimic the symptoms of azoxymethane (a colorectal carcinogen) exposure (Bonanomi et al., 2022), and they also tend to rapidly cross placental membranes and bioaccumulate in fetal tissues (Fournier et al., 2020). The relationship between exposure to particulate plastics and adverse birth outcomes is vague. Pathways for neurotoxicity have also been suggested (Prüst et al., 2020).

Karbalaie et al. (2018) have attempted a description of human toxicological impacts and constructed the possible endpoints of toxicity for human exposure to include increased mucus production, cardiovascular disease, asthma, and cancer (Karbalaie et al., 2018). Furthermore, Jeong and Choi (2019), and Kontrick (2018) have noted that toxic effects leading to mortality, reproductive failure, energy depletion, and growth retardation are mainly due to oxidative stress posed by particle exposure (Schirizzi et al., 2017). Human health risk assessment for particulate plastics is imperative considering the broad responses these materials can elicit in the human body. The inconsistent, unsystematic, uncoordinated and unvalidated procedures at present however are likely to incorrectly estimate the bias associated with such measurements. Further research is needed to validate pathways that can meaningfully and systematically provide estimates that are reliable and unambiguous.

#### 5.4. Future research needs for human health risk assessment

Human health risk assessments of particulate plastics in drinking water are still very novel and insufficient, and further research is needed to characterise their safety. For instance, there is a controversy over an appropriate fit-for-purpose dose unitization (whether count, weight, or size distribution) that should be used for dose-response estimations (Coffin et al., 2022a; Koelmans et al., 2022; Kooi et al., 2021; Mohamed Nor et al., 2021; Senathirajah et al., 2021) and whether current analytical techniques are competent at estimating micro, sub-micro and nano concentrations in environmental media and biological specimen (Caldwell et al., 2022; Caputo et al., 2021; Coffin et al., 2022b). Beside the problem of estimating actual doses, reference doses and cancer slope factors (pathway unit risks) are also lacking. Whether these factors can be validly estimated for such complex structures as particulate plastics is also a question of time. The physical and chemical diversity of different particles is another source of uncertainty (Coffin et al., 2022a; Koelmans et al., 2022; Kooi et al., 2021). However, the biological behaviour of particles has been studied, although with limited scope. The sheer physical size of micro, sub-micro and nano particles means that they can be carried in potable water, posing the risk of ingestion and dermal absorption. Following uptake, they become bioavailable and may be absorbed. In order to provide for their risk characterization, it may be relevant to differentiate between environmental particulate plastics in the general notation of primary and secondary microplastics, nano-plastics and sub-nanoplastics; systemic particulate plastics that will reside in biological systems and tissues upon uptake; and cytoplastics that may be consigned to cellular system or translocate between the cell and the system.

#### 6. Particulate plastics in fresh and drinking water in sub-Saharan Africa

Due to the stagnation of Sub-Saharan Africa (SSA) in achieving the targets of SDG 6.1, it is imperative to consider water security and source water protection throughout the region. The SSA is estimated to produce some 17 million tons of plastic waste annually (Ayeleru et al., 2020; Ike et al., 2018). With limited capacity for recycling, material recovery and reuse, significant proportions of this waste is released into the environment. Nigeria and Ghana have been noted as some of the high emitters within the region (Dumbili and Henderson, 2020; Miezah et al., 2015). In Ghana for instance, waste composition studies have estimated nearly 13,000 tons of waste emissions per day with the plastics fraction constituting some 15% (Miezah et al., 2015; Seshie, 2015; Tawiah et al.,

2016). Accra, the national capital and the most populous and urbanized city in Ghana, alone is deemed to produce an estimated 270,000 tons of various plastic waste annually, half of which is uncollected and ends up on aquatic and terrestrial biomes (Solheim and Jensen, 2019). Major freshwater river systems such as the Densu river which serve the drinking water needs of vast populations in Accra have been contaminated with microplastics, raising concerns about the engineering capabilities of drinking water treatment headworks in dealing with plastic materials and their adjuvants (Blankson et al., 2022). Similar results have been reported in other hotspots such as Nigeria, Senegal, Cameroun, Mozambique, Tanzania, Kenya and South Africa (Okeke et al., 2022; World Wide Fund for Nature, 2022). These plastics and their by-products may be potential sources of contamination of drinking water.

Research into particulate plastics in Africa is generally very sparse and mainly consigned to marine systems with limited information on drinking water (Aragaw, 2021). The bulk of current research is manifested in Europe, Asia, the Middle East and the Americas as shown in Fig. 5.

Particulate plastics maybe nonpoint source pollutants on land and in water. Verster et al. (2017) have opined that microplastics-infested agricultural land and drinking water may pose public health challenges to the general population. In many developing countries, many rural and peri-urban communities drink directly from surface water resources such as riverine systems and streams. These open natural systems are also exposed to and influenced by anthropogenic activities that introduce particulate plastics contamination. In recent times, L/HDPE and PET packaged water serve the potable water needs for large populations in Africa (Dzodzomenyo et al., 2017; Guzmán and Stoler, 2018; Wardrop et al., 2017). Ibeto et al. (2021) sampled low numbers of polyethylene, polycynyl chloride, polyethylene terephthalate, and poly dimethyl siloxane microplastics in plastic packaged drinking water in Nigeria using scanning electron microscopy tandem energy-dispersive X-ray diffractive spectroscopy, and 11 µm filter paper. Although the method employed in this study had the propensity of losing microplastics quantification, the results re-inforced the need to broaden the scope of water safety plans in developing countries. Unfortunately, there are no national standards or guidelines for evaluating environmental pollution of particulate plastics, and health risk assessments of fresh and potable water particulate plastics are very rudimentary. In the face of the uncertainties regarding the quantification of particulate plastics and the lack of risk factors for hazard characterization, it is important to reinforce source water protection programs that avoid ground and surface water plastic pollution.

#### 7. Future of plastics in Africa

The demand for packaging plastics has spearheaded the growth in the plastics market in Africa and an upsurge in waste plastics, especially single-use plastic materials. Largely, waste management programs have been motivated by aesthetic concerns and not a predilection for resource valorisation (Akindele et al., 2019; Nel et al., 2021). Plastic materials are indispensable, at least not until sustainable alternatives are available. Viable economic management of plastic streams are vital in ensuring that waste plastics are diverted from ecological systems. Plastic pollution is inextricably linked to poor end-of-life management and the lack of a plastics circular economy.

Adequate management programs that prioritise macroplastics management, the environment and ecological pollution due to particulate plastics, and the hazardous chemicals of plastic origin, may require novel approaches to achieve net zero pollution targets. Lightweight plastic ban instruments are widespread in Africa but poor policing mechanisms of the policies, and strong pro-plastic lobbying groups have led to the bans being moribund. Mechanical recycling technology, which is being phased out in most developed countries, is common in most African nations. On the other hand, chemical recycling is still very novel

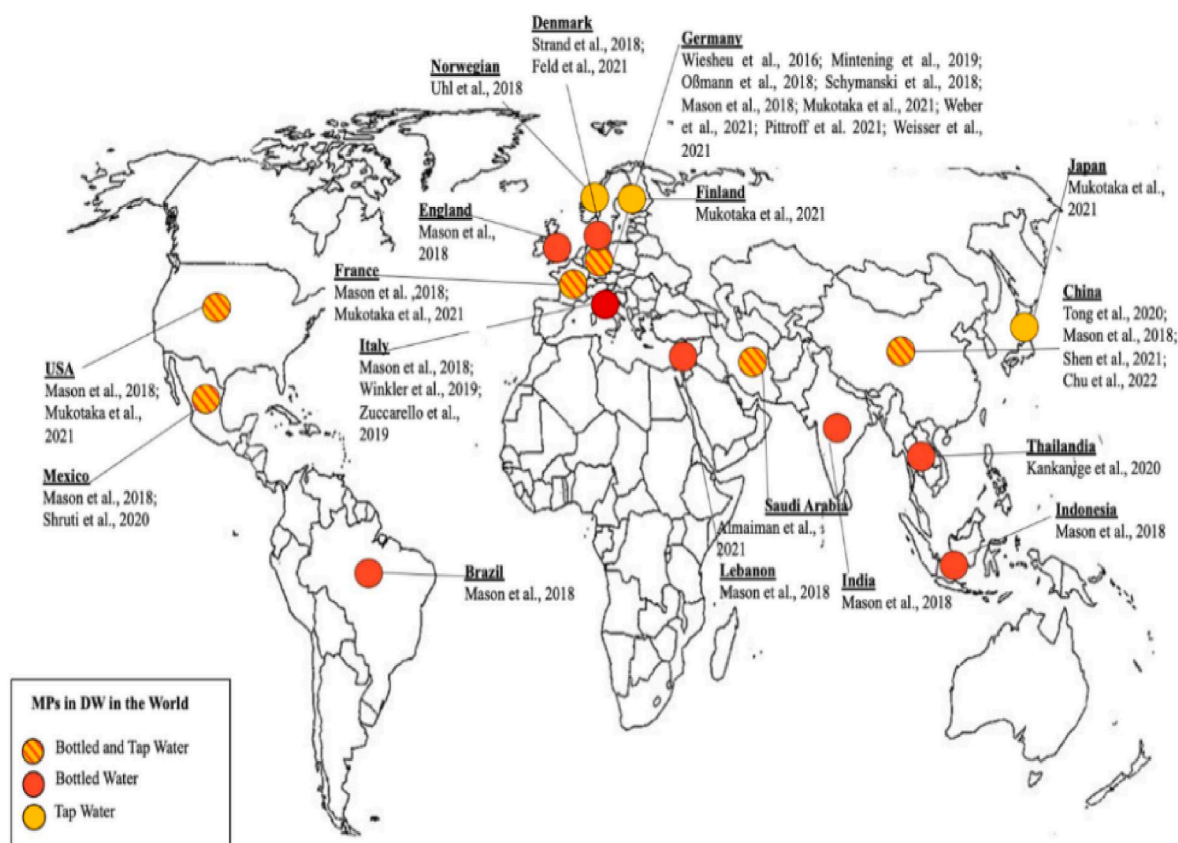


Fig. 5. Global representation of drinking water particulate plastics research (Gambino et al., 2022).

in Africa but may provide useful chemicals and alternative sources of energy to improve fuel economies, and feedstock for other industrial applications (Rai et al., 2021; Wang and El-Sepelgy, 2021). This will complement mechanical processes to optimise end-of-life management options. The use of prodegradant catalysts have been championed across the continent to improve the degradability of plastics. Degradation of these materials is dependent on temperature and luminous intensity, and may lead to the emission and accumulation of particulate plastics.

Biocomposite materials that are sensitive to microbial degradation are less developed but may also prove useful in avoiding the environmental and ecological dangers posed by synthetic plastics (Ahmaditabatabaei et al., 2021; Liu et al., 2021b). Completely degradable bioplastics are the most likely green alternative if long term protection is to be guaranteed. However, these technologies are quiet virgin in an African context. Recent laboratory scale experiments may prove useful in the abstraction of particulate plastics during water treatment. For instance, magnetized techniques have been proposed by Shi et al. (2022) although significant optimisation of the procedures will be required for scale-up. Photo-mediated degradation of particles has also been explored by Ariza-Tarazona et al. (2020) and Acuña-Bedoya et al. (2021), as well as nanomembrane filters (Yang et al., 2022) and electrocoagulation mechanisms (Shen et al., 2022) to better effects. These developments are very promising, and collaboration among scientists, and increased funding for research and development are required to design and scale up.

It is important that African countries identify areas of research and industrial collaboration considering the fact that plastics pollution is transboundary and aquatic pollution affects all mankind. The exigencies of transboundary plastics pollution of terrestrial, aquatic and atmospheric systems and their externalities on human health, ecological systems, biodiversity, and climate will require regional and international cooperation, and interdisciplinary approaches. The African

solution may lie in Simon and Schulte (2017) proposition to negotiate a continent-wide convention that tackles plastic pollution where it originates, foster innovation for more sustainable plastics, and support countries to enhance their domestic waste collection and recycling systems, and circular economy initiatives.

## 8. Concluding remarks and recommendations

The presence of particulate plastics in drinking water has been well documented in the limited literature worldwide. Uncertainties do exist in testing methodologies, data reporting and risk assessments. Particle diversity, dose-response estimation and lack of exposure thresholds, and uncertainties in toxicological hazards have impaired the risk assessment framework for internalized particulate plastics. The current review identifies that research into drinking water particulate plastics is a new scientific discipline that may prove useful in establishing total ingestion exposure. The diversity in biological modes of action and transport behaviour of particulate plastics is an important attribute for risk characterization. We recommend the need to consider a holistic and a more comprehensive approach for the evaluation of particulate plastics exposure in drinking water and other environmental matrices using quality-assured processes. At the continental level, we propose an African framework that commits to a circular plastics program by considering: improvements in waste separation and collection, improvements in recycling rates and increasing demand for recycled products, increasing penetration of bioplastics, advocating for the manufacturing of cleaner packaging through product re-engineering, advocating for reusable plastics rather than disposables, and transitioning towards completely biologically degradable plastic substitutes.

## Credit author statement

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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