Microplastics in Inland African Waters: Presence, Sources, and Fate

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Abstract As the birthplace of our species, the African continent holds a unique place in human history. Upon entering a new epoch, the Anthropocene defined by human-driven influences on earth systems, and with the recognition that plastic pollution is one of the hallmarks of this new age, remarkably little is known about the presence, sources, and fate of plastics (and microplastics (MPs)) within African waters. Research in marine regions, most notably around the coast of South Africa, describes the occurrence of MPs in seabirds and fish species. More recently environmental sampling studies in the same area have quantified plastics in both the water column and sediments. However, despite Africa containing some of the largest and deepest of the world's freshwater lakes, including Lakes Victoria and Tanganyika as part of the African Great Lakes system, and notable freshwater rivers, such as the River Congo and the Nile, the extent of MPs within the inland waters remains largely unreported. In the only study to date to describe MP pollution in the African Great Lakes, a variety of polymers, including polyethylene, polypropylene, and silicone rubber, were recovered from the gastrointestinal tracts of Nile perch (*Lates niloticus*) and Nile tilapia (*Oreochromis niloticus*) fished from Lake Victoria. The likely sources of these plastics were considered to be human activities linked to fishing and tourism, and urban waste. In this chapter we discuss the need for research focus on MPs in Africa and how what has been described in

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the coastal regions and other freshwater environments can be applied to inland African waters. The aforementioned study in Lake Victoria is used to exemplify how small-scale investigations can provide early indications of MP pollution. Lastly we discuss the current challenges and future needs of MP research in African freshwaters.

Keywords Africa, African Great Lakes, Freshwater, Microplastics, MP sampling

1 Introduction

1.1 Africa, the Anthropocene, and Plastic Pollution

As the birthplace of our species, the African continent holds a unique place in human history. Current scientific consensus places the evolution of modern humans in East Africa approximately 200,000 years ago from where they successfully dispersed approximately 72,000 years ago during the late Pleistocene [1, 2]. From here our species continued to spread and over the next 50,000 years or so colonized the majority of the Earth's land surface. Fast-forward through the following epoch, the Holocene, which is regarded as being relatively stable in terms of climate, and we arrive at a point in time in which humankind have established themselves as the dominant force and major driver for environmental change. Accordingly a new era is said to have now dawned – the Anthropocene [3, 4]. While the exact start date of the Anthropocene is subject to much current debate, the advent of the industrial age (ca. 1800s) changed the dynamics between humans and the environment. The Anthropocene is thus defined by human actions which perturb the Earth's land, oceans, and biosphere [5]. These dramatic effects include climate change, ocean acidification, deforestation, and plastic pollution.

Plastics (and microplastics, MPs, defined as <5 mm in size) are considered a hallmark of this new anthropogenic age, having become widely used in the last 60 years [6], and are now a ubiquitous pollutant found worldwide and in all aquatic compartments (surface waters, water column, and sediments) and numerous animals (invertebrates, fish, seabirds, and marine mammals) [7]. Up until recently MP pollution had been viewed solely as a marine issue, but there is now an increasing amount of information regarding the presence of MPs in freshwaters [8, 9]. MPs have been sampled from both freshwater lakes, such as Lakes Erie, Huron, and Superior in Canada [10], Lake Geneva in Switzerland [11], and Lake Garda in Italy [12], and rivers, such as the River Thames in London (UK, [13]), River Seine in Paris (France, [14]), and the Danube [15], to name but a few. In this last study, the mass and abundance of drifting plastic items in the Austrian Danube were found to be higher than those of larval fish [15], which is an indication of the magnitude of the problem. However, there is remarkably little information on the presence of MPs in the freshwaters of Africa – the place where it all started for humans!

In this chapter we begin by outlining the scope for plastic pollution in African inland waters, both through the nature of the water bodies and the human pressures they face. We then focus briefly on the marine and estuarine MP research that has been conducted in Africa. There are only two studies that have investigated the prevalence of plastics in African freshwaters, specifically the Tanzanian waters of Lake Victoria, Ngupula et al. [16] and Biginagwa et al. [17], and only the latter is focused directly on MPs. They are exemplified as case studies, which, in addition to providing useful data, may also be a template for similar research in other African freshwater bodies. Lastly, we discuss the current challenges and knowledge gaps and future research needs that require attention in order to gain a better understanding of the presence, sources, and fate of MPs in inland African waters.

1.2 African Freshwaters and the Potential for MP Pollution

The African continent contains some of the most famous and notable freshwater bodies in the world. The River Nile, which is the second longest river, has been described as the "donor of life to Egypt" [18], and the River Congo is the second largest by river discharge (in both cases the Amazon is number one) and also the world's deepest river. Lakes Victoria, Tanganyika, and Turkana are perhaps the three most well-known of the African Great Lakes that are located in East Africa. Lake Nasser is a vast man-made reservoir that was created by the construction of the Aswan Dam across the River Nile. Each of these freshwater bodies, identified in Fig. 1, supports significantly sized populations (see Table 1a, b). The city of Cairo, through which the Nile flows, will have a population of over 20 million inhabitants by the year 2020 according to United Nations Sources [19]. The River Congo flows through the capital city of the Democratic Republic of the Congo, Kinshasa, with a population of over 14 million, and the Lakes Victoria and Tanganyika both have on their banks urban centers of >1 million people. Many of Africa's cities have undergone rapid urban expansion [20], with sub-Saharan urban growth averaging 140% between the 1960s and the 1990s, at a rate 10 times faster than OECD countries and 2.5 times than the rest of the developing world [21].

Inevitably, the pace of increase has placed pressure on urban services and not least in the management of solid waste, where it is common in the developing world for municipalities to be short of funds, deficient in institutional organization and interest, have poor equipment for waste collection, and lack urban planning [22, 23]. Among this waste are plastics. Plastics, as we know, are used in a variety of products including packaging, bags, bottles, and many other short-lived products that are discarded within a year of production [6]. In some parts of the world, plastic recycling procedures are well established, but in African countries, even when reuse and/or recycling practices are present, they often lack legal foundation and are therefore conducted on an ad hoc basis [24]. Thus much solid waste ends up in landfills or is subject to illegal dumping. In proximity to freshwater systems, plastic waste then has the potential to enter the aquatic environment where subsequent degradation can form MPs. The link between urban waste and MPs has been established in the freshwater MP literature [10, 11, 13, 15], but to date there is

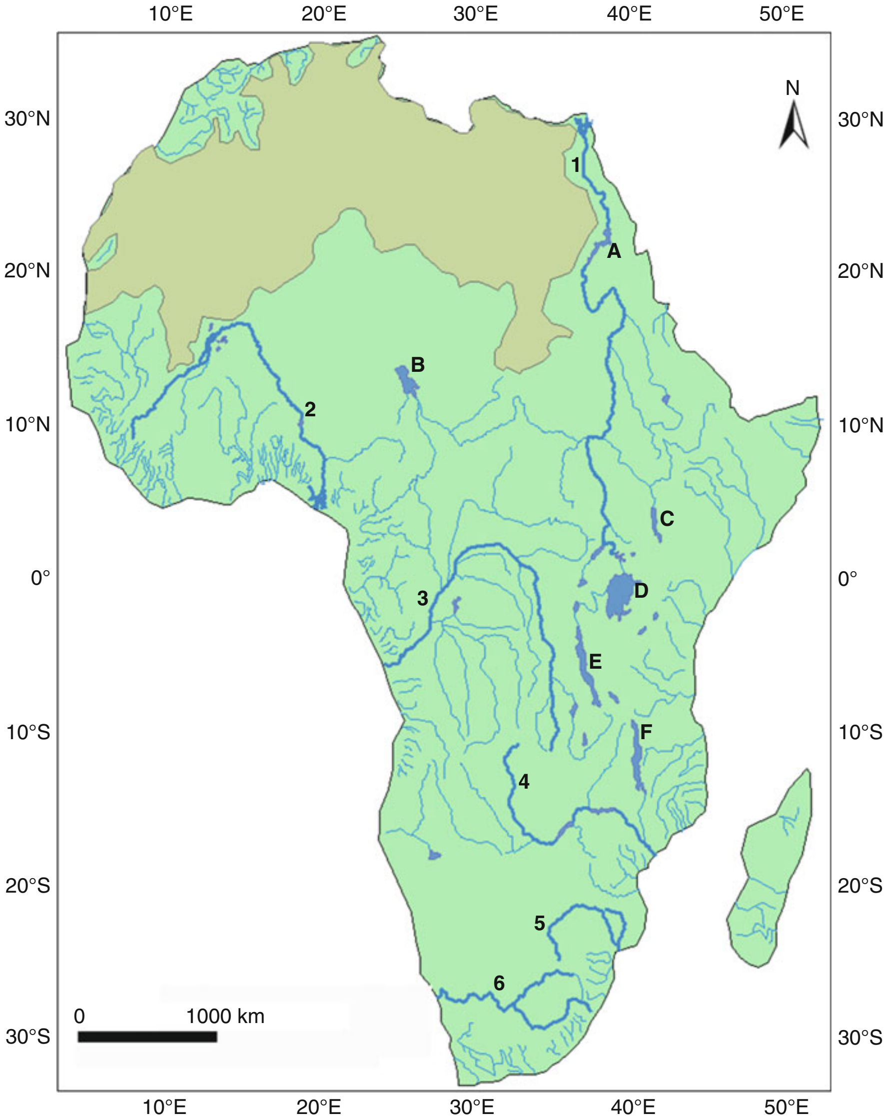

Fig. 1 Map of the African continent showing major freshwater bodies (rivers numbered 1–6 and lakes lettered *A*–*F*). Water bodies and their characteristics including highly populated neighboring urban centers can be found in Table 1

little information on this specific to African freshwaters. Contributions to MP concentrations may also be from fishing and tourism activities [25] which are commonly linked to freshwaters. Given the magnitude of Africa's freshwater bodies and the populations and activities they support, the likelihood for MP pollution in these waters is substantial.

Table 1 Major African freshwater bodies, their characteristics, and neighboring urban centers (>0.3 million people) with estimated populations (in 2020). (a) Major rivers depicted on Fig. 1 (numbered 1–6) are described by the location of river mouth, length, and average discharge. (b) Major lakes depicted on Fig. 1 (lettered A-F) are described by the counties in the basin, surface area and water volume

River[(a)]		Flows through	Length (km)	Average discharge (m^3/s)	Major urban centers and estimated population size in 2020 (million)[a]
1	Nile	Egypt, Sudan, South Sudan, Uganda	6,853	2,830	Cairo (20.57), Alexandria (5.23), Aswan (0.34) (all Egypt); Khartoum (5.91) (Sudan); Juba (0.40) (South Sudan)
2	Niger	Guinea, Mali, Niger, Benin, Nigeria	4,180	5,589	Bamako (3.27) (Mali); Niamey (1.32) (Niger); Lokoja (0.66) (Nigeria)
3	Congo	DR Congo, Congo	4,700	41,000	Kinshasa (14.12), Kisangani (1.25), Mbandaka (0.44) (all DR Congo); Brazzaville (2.21) (Congo)
4	Zambezi	Angola, Zambia, Zimbabwe, Mozambique	2,574	3,400	No urban centers >0.3 m people
5	Limpopo	South Africa, Botswana, Zimbabwe, Mozambique	1,750	170	No urban centers >0.3 m people
6	Orange	South Africa	2,200	365	No urban centers >0.3 m people
Lakes[(b)]		Basin countries	Surface area (km^2)	Water volume (km^3)	Major urban centers and estimated population size in 2020 (million)[a]
A	Nasser	Egypt, Sudan	5,250	132	Aswan (0.34) (Egypt)
B	Chad	Chad, Cameroon, Niger, Nigeria	1,350	72	N'Djaména (1.54) (Chad)
C	Turkana	Kenya, Ethiopia	6,405	203.6	No urban centers >0.3 m people
D	Victoria	Tanzania, Uganda, Kenya	68,800	2,750	Kampala (2.39) (Uganda); Mwanza (1.12) (Tanzania)
E	Tanganyika	Burundi, DR Congo, Tanzania, Zambia	32,900	18,900	Bujumbura (1.01) (Burundi); Uriva (0.57) (DR Congo)
F	Malawi	Malawi, Mozambique, Tanzania	29,600	8,400	No urban centers >0.3 m people

[a]Source: United Nations, Department of Economic and Social Affairs, Population Division (2014) [18]

Despite the lack of scientific confirmation of MPs in Africa's freshwaters, it would be unfair to say that there is a lack of recognition of the plastic issue. On the contrary, there has been a great deal of research conducted on the presence of MPs within the marine and estuarine environment (described in the following section), and also, there has been much progress made on reducing and banning the use of plastic bags in some countries. This progress has not been made solely to reduce the plastic waste but also on the grounds of environmental and public health. Improperly discarded plastic bags have been shown to block gutters and drains which create storm water problems and collect water which provides a breeding ground for mosquitos that spread malaria, and the use of bags as toilets has been linked to the spread of disease [26, 27]. The government of South Africa introduced levies on the use of plastic bags in 2003 [28], in 2005 Rwanda imposed a ban on the use and importation of plastic bags of <100 microns thick, and Tanzania similarly imposed a ban based on thickness in 2006 [27]. Such measures may not always be successful as in South Africa levies were not predicted to reduce the plastic bag litter stream [28]. Subsequently the actions taken, while positive, may have little impact in terms of the potential for MP pollution in African freshwaters. However, the scale of the problem first needs to be assessed, and in this regard, studies conducted in marine and estuarine waters may show the way forward.

2 Presence of MPs in African Marine and Estuarine Environments

In comparison to the rest of Africa, significant knowledge has been gathered about the presence, sources, and fate of plastics and MPs in the coastal regions around South Africa and their biota. The earliest documented reports of plastics are from the mid- to late 1980s with Ryan [29] having sampled the sea surface water off the southwestern Cape province between 1977 and 1978 with a total of 1,224 neuston trawls that found a mean plastic density of 3,640 particles km^{-2} with the majority of the particles in the MP range. Commonly found types were fragments, fibers, and foamed plastic particles with polyethylene being a predominant polymer [29]. A follow-up study [30] conducted at 50 South African beaches in 1984 and 1989 found a significant increase in the mean MP density from 491 m^{-1} in 1984 to 678 m^{-1} 5 years later. Analysis of the distribution of MPs found that inshore currents rather than local sources were responsible for the variation in abundances between beaches. Conversely, in the case of macroplastics, it was the local sources that had the greater influence. More recent research conducted by Nel and Froneman [31] reached the same conclusion regarding the primary influence on the distribution of MPs in both sediment and water. Across 21 sampling locations along South Africa's southeastern coastline, comprising both bay and open coast areas, with both sediment and water samples analyzed for MP abundance, the authors found that MP densities in general did not significantly vary between sites in either matrix. As with the study conducted 25 years prior, the conclusion was that water circulation rather than proximity to land-based sources was main driver to MP abundances in coastal regions [31].

Biological sampling in this region has also revealed a number of interesting details regarding the fate of marine plastics. Plastic particles were found in more than half the seabirds predominantly sampled off Southern Africa and African sector of the Southern Ocean [32]. The size of the ingested particles was related to the body size of the bird, and smaller species exhibited a higher incidence of plastic ingestion. Dark-colored particles were more abundant suggesting a selection for easily visible particles rather than transparent ones. Omnivorous species were the most likely to confuse plastics with prey items, whereas feeding specialists were less likely to mistake plastics for food, unless they shared a resemblance [32]. A comparison of this historic dataset with a more recent sampling period (1999–2006) revealed a decrease in virgin pellet ingestion, but no overall change in total plastic ingestion [33]. This decrease suggested a change in the make-up of small plastic debris at sea in the intervening period.

Studies in the estuarine environment are less common than marine studies and, like freshwater research on MPs, have only recently started to gain momentum. However, estuaries provide pathways for the transport of MPs from catchments to the oceans, notably in urban areas where estuarine waters serve as industrial outflows or fishing grounds [34, 35]. The characterization of MPs in five urban estuaries of Durban (KwaZulu-Natal, South Africa) found the highest concentrations in sediments collected from Durban harbor, which included cosmetic microbeads and fibers [35]. Possible sources were thought to include the several rivers that flow through Durban's industrial suburbs and enter the harbor, the industrial companies that use plastic powders and pellets around the harbor, and the closeness of dry docks where ship repairs take place. The fate of these plastics was revealed in a follow-up study by the same authors looking at plastic ingestion by the estuarine mullet (*Mugil cephalus*) in Durban harbor [36]. Plastic particles were found in the digestive tracts of 73% of the sampled fish, with more than half of the recovered plastics in the form of fibers and approximately one-third as fragments. Plastic concentrations found in the mullet were higher than those reported elsewhere for other species, and it appears that, as with omnivorous seabirds, the nonselective feeding mode of *M. cephalus* (i.e., ingestion of sediments) was a contributing factor.

Studies into South Africa's plastic and MP pollution are particularly pertinent as the country is ranked within the top 20 counties with the highest mass of mismanaged plastic waste [37]. Other African countries are also on the list, and although focused on marine debris, the relevance to freshwaters should not be ignored.

3 Presence, Sources, and Fate of MPs in Inland African Freshwaters

3.1 Presence of MPs in Freshwaters

The presence of MPs has been extensively reported in the marine environment [38–40], including that of South Africa's coast (as described in the previous section). In comparison, describing MPs in freshwaters is still in its infancy with the majority of research only arriving in the last 5 years [9]. Thus, only a few studies have investigated the occurrence of MPs in freshwaters with research conducted in the vicinity of urbanization and industrialization, such as Laurentian Great Lakes in North America [10] and Lake Geneva in Switzerland [11], as well as in more remote locations, such as Lake Hovsgol in Mongolia [25] and Lake Garda in Italy [12]. Not only do these studies show that MPs are present in freshwaters, but also relate the type of plastics found to their likely sources.

In the Laurentian Lakes (Lakes Superior, Huron, and Erie), MPs were found in 20 out of 21 surface samples, and in many of the tows, the most notable MPs were multicolored spherical beads that were determined to be polyethylene in composition. Shape, size, and composition were comparable to the microbeads used in exfoliating facial cleansers and cosmetic products and were likely to originate from nearby urban effluents [10]. Although there have been efforts to raise scientific, regulatory, and public awareness to ban the use of microbeads [41–43], successfully in some countries, the Canadian Great Lake study demonstrated that they are already abundant in the environment, and in the Laurentian lakes, "hot spots" were found where lake currents converge. Logically, it would be expected that remote lakes with lower population densities would have less plastic pollution than freshwaters near urban centers, but in case of Lake Hovsgol, the remote mountain lake in northwest Mongolia near the Russian border, the opposite was true. An MP density of 20,264 particles km^2 was averaged from nine transacts making the lake more polluted than Lakes Huron and Superior. No microbeads were found with fragments and films instead being the most abundant MP shapes. The shoreline was dominated by discarded household waste (bottles, plastic bags) and fishing gear, and the likely source of the pelagic MPs was the degradation of this shoreline debris [25]. Thus even low population densities can cause significant levels of MP pollution in the absence of waste management infrastructures. Taken together it appears that plastics recovered from freshwaters in different parts of the world closely reflect the anthropogenic activities and waste generated by the local populations. Although this would seem obvious, further research is required to verify this link with the aim of more specific waste management relating to the nature of plastic pollution within a given location.

To date only two studies have attempted to document the presence of plastic debris in African freshwaters [16, 17], and only one specifically focused on MPs [17]. Both studies were conducted in the Tanzanian waters of Lake Victoria, and in the following sections, we describe them as case studies. In addition to providing valuable baseline data for MPs in Lake Victoria, these investigations may serve to inform how research could be conducted in other African freshwater bodies.

3.2 Plastics in the Tanzanian Waters of Lake Victoria

Lake Victoria is the world's second largest freshwater lake by area (the largest being Lake Superior in North America) and has been described as eutrophic and polluted due to human influences within the catchment area [44]. The area surrounding the lake is among the most densely populated in the world, and this population growth is set to continue – by the year 2020, an estimated 53 million people will inhabit the lake basin [45]. The majority of economic activities in the region are associated with the lake with one of the most important being fishing.

Case Study I details the work of Ngupula et al. [16] in which the authors documented presence and distribution of solid waste including plastic bags and fishing gear at six depth strata reaching 80 m below the surface. Thus, while they did not specifically look for MPs in the waters of Lake Victoria, the work of these authors greatly increases our understanding of where MPs originate from in the lake system. In the second case study by Biginagwa et al. [17], the ingestion of MPs by resident fish species in Lake Victoria was used in place of environmental sampling. The recovery of MPs from the gastrointestinal tracts of Lake Victoria Nile perch (*Lates niloticus*) and Nile tilapia (*Oreochromis niloticus*), and their subsequent characterization, provided the first evidence of MPs within African inland freshwaters.

3.2.1 Case Study I: Abundance, Composition, and Distribution of Solid Wastes in Lake Victoria

To determine the vertical distribution of solid wastes in Lake Victoria, the waters were categorized into three main ecological zones: (1) the nearshore, which is described as highly influenced by anthropogenic input and was sampled at depths of $<$10 m and 10.1–20 m; (2) the intermediate zone which is moderately influenced by the catchment and was sampled at depths of 20.1–30 m and 30.1–40 m; and (3) the deep offshore waters which are the most isolated from the human activities and were sampled at depths of 40.1–50 m and then $>$50.1. The maximum depth of Lake Victoria is 80 m; thus, this last depth stratum extended to bottom trawls. Across these three zones and six strata, 68 samples were taken in total during two periods, May and late September to early October 2013. Trawls were conducted at three knots and debris collected by 4 mm mesh trawl net.

Plastic debris was found at all depths and all sampling locations. Across all trawls, the dominant waste types originated from fishing activities; multifilament gillnets compromised 44% of all debris, monofilament gillnets (42%), longlines and hooks (7%), and floats (1%). Plastic bags (4%) and clothing (2%) accounted for the remaining solid waste. Gillnets, which compromised more than 80% of all the debris found and 96% of waste in the fourth depth strata, are constructed using synthetic fibers, and although nylon was used in the 1960s, newer materials, such as ultrahigh-molecular-weight polyethylene (UHMWPE) or polyethylene terephthalate (PET), are now commonplace as they are cheaper, are more durable, and require less maintenance. Multifilament gillnets are used in the fishing of Nile perch, while monofilaments are used for catching tilapiine species, including Nile tilapia. Both species were found to contain MPs in their intestinal tracts, as described in Case Study II [17].

There were only minor differences in the abundance by weight of debris sampled from the different depths, and of the six waste types identified, the proportion found at each depth did not vary to any great degree, with the exception of the bottom strata in which longlines and hooks (67%) were most abundant. Of the three ecological zones, the intermediate zone (20.1–40 m) contained most waste and is also known to have the highest levels of fishing activities; thus, within this zone, there was a reduced abundance of clothing and plastic bags. Fishing activity appears to be the major source of solid (plastic) waste in Lake Victoria, but land-based waste was not accounted for due to the inability to trawl at shallow depths (<4 m) in the nearshore. Land-based waste is often an important component of marine waste and through tidal action is transported to the lower depths of the sea [46]. However, without strong currents, this mechanism of circulating waste is ineffective within the lake environment. Nevertheless, within shallow waters, land-based waste would undoubtedly be important.

While not specifically focusing on the abundance of MPs, this study demonstrates that plastic waste is present at all levels of Lake Victoria and is strongly linked to fishing activities and discarded fishing gear. Though authors do not discount other sources including land runoff and transportation of cargo, the limitations of the study do not allow these to be investigated further.

3.2.2 Case Study II: Recovery of MPs from Lake Victoria Nile Perch and Nile Tilapia

A number of studies have used the ingestion of MPs by resident fish species as a marker of MP pollution. Lusher et al. [47] found that marine pelagic and demersal fish sampled from the English Channel readily consume plastics, and Sanchez et al. [48] similarly reported, for the first time in freshwaters, that wild gudgeons (*Gobio gobio*) inhabiting French rivers ingest MPs. Using Nile perch (*Lates niloticus*) and Nile tilapia (*Oreochromis niloticus*) as proxies for environmental MP contamination in Lake Victoria, a small-scale study was conducted in the Mwanza region of Tanzania, located on the Lake's southern shore (Fig. 2). Both species are economically and ecologically important and were introduced to Lake Victoria in the 1950s and 1960s with the aim of supplementing native fish populations that had declined due, in part, to overfishing [49]. However, this introduction was detrimental to the native species, particularly the native tilapiine species such as the Victoria tilapia

Fig. 2 Map of the Lake Victoria study area showing the Mwanza region. (**a**) Nile perch and Nile tilapia were purchased from the harbor market at Mwanza (regional capital). The local fishing area extends across the Mwanza Gulf and to Ukerewe Island. Inset Lake Victoria (LV) bordered by Uganda, Kenya, and Tanzania. The Mwanza region located on the southern shore of Lake Victoria is highlighted. (**b**) Urban waste in Mwanza, including plastic debris, collects in drainage ditches which are a potential source of plastic pollution in Lake Victoria. (**c**) Nile Tilapia used in this study (photographed prior to dissection) were purchased from the market

(*Oreochromis variabilis*) and Singidia tilapia (*Oreochromis esculentus*), which subsequently disappeared from parts of the lake [49, 50]. Thus Nile perch and Nile tilapia have established themselves as dominant commercial and ecological species and therefore represent logical choices by which to monitor MP pollution in the area. Moreover, their differing feeding habits could provide additional information by which to contextualize plastic ingestion. Nile perch are predatory fish feeding on *haplochromine* cichlids and gastropod snails, whereas Nile tilapia are omnivorous with a diet consisting of plankton and fish.

In March 2015, 20 fish of each species were purchased from Mwanza harbor market, where fish are caught and sold daily. The fishing territory for both species extends to Ukerewe Island (the largest island in Lake Victoria) to the North of Mwanza and across the Mwanza Gulf to the neighboring district of Sengerema (Fig. 2). Nile perch and Nile tilapia were 46–50 cm and 25–30 cm in length and 500–800 g and 500–700 g in weight, respectively. For each fish, the dissection of the entire gastrointestinal tract (buccal cavity to anus) was conducted on site. All efforts were made to eliminate sample contamination with separate clean dishes used for each fish and thorough cleaning of dissection utensils between samples. A preliminary examination was made of each gastrointestinal tract, and in the case of Nile perch, undigested gastropods and cichlids were removed. Gastrointestinal tracts and their contents were then individually preserved in 96% ethanol and transported to laboratory facilities at the University of Dar es Salaam (Dar es Salaam, Tanzania), a journey of approximately 1,150 km. In the laboratory, NaOH digestion (10 M NaOH at 60°C for 24 h) was used to isolate plastic litter from the organic tissue. The NaOH method has been shown to digest organic matter with an efficacy of >90% [51], and the tests of this protocol prior to its use confirmed such high efficiencies ($96.6 \pm 0.9\%$, $n = 5$, data not shown). Importantly, NaOH digestion has a minimal impact on the chemical and physical states of plastics, especially when compared to strong acid digestion which, while also being an effective digestant of organic matter, can discolor or degrade plastics. Post-digestion, plastics, and a minimal amount of partially digested tissue were rinsed from the NaOH through 250 μm mesh stainless steel sieves under running water and placed on filter paper to dry. Samples were then brought to the laboratory (Roskilde University, Denmark), and suspected plastic pieces were separated from tissue residue under light dissection microscope. The chemical composition of all suspected plastics was identified nondestructively by attenuated total reflectance Fourier transform infrared (ATR-FTIR) spectroscopy, a standard analytical technique for identifying the chemical composition of samples larger than 0.5 mm. Scans were run at a resolution of 2 cm^{-1} between 4,000 and 650 cm^{-1} on a Bruker Alpha FT-IR instrument (Bruker, Billerica, MA, USA) fitted with a diamond internal reflectance element. Spectra were compared with standard references on the same instrument and processed using Opus software supplied by Bruker.

In total, suspected plastics were recovered from the gastrointestinal tracts of 11 perch (55%) and 7 tilapia (35%). However, some plastics were too small (i.e., <0.5 mm) to have their chemical structure confirmed by ATR-FTIR. In addition, spectroscopy of some suspected plastic samples showed that their compositions most closely resembled cellulose, suggesting these samples were likely plant material or paper originating from perhaps newspaper, tissues, or cigarette filters. Thus 20% of each fish species (i.e., four individuals) contained confirmed MPs within their gastrointestinal tracts. The polymers recovered from the fish were polyethylene, polyurethane, polyester, copolymer (consisting of polyethylene and polypropylene), and silicone rubber (Fig. 3). The common use of such materials includes packaging, clothing, food and drink containers, insulation, and industrial applications (Table 2). Given the dimensions of the recovered plastics (0.5–5 mm, Fig. 3), it is likely that the MPs ingested by the fish are secondary MPs which have resulted from the degradation and breakdown of larger plastic pieces [38]. A likely source of the input of such materials into the Mwanza Gulf area is from the drainage ditches that are filled with urban waste, including plastic products (Fig. 2). This may be a particular problem during heavy rain when input into the lake is increased. In common with other studies conducted at freshwater sites [10, 25], it appears that the nature of the plastic pollution is related to the usage and waste by the local human population.

This work provided the first evidence that MPs are present in the African Great Lakes and that they are ingested by economically important fish species. In addition to confirming the ingestion of MPs by freshwater fish species [48], the chemical composition of the MPs was determined. However, this is only a preliminary study and only limited conclusions can be drawn. With plastics confirmed in only 20% of both species, the study likely underestimates the true extent of plastic ingestion by Nile perch and Nile tilapia, especially when considering the constraints of ATR-FTIR analysis and the inability to confirm the identity of the smaller-sized suspected "MPs." Similarly, it is not possible to determine whether the feeding preferences of the two species effected their ingestion of plastics. Thus, while this study provides evidence for the ingestion of secondary MPs by fish populations, it is clear that further research needs to be undertaken in Lake Victoria to fully characterize the extent of MP pollution.

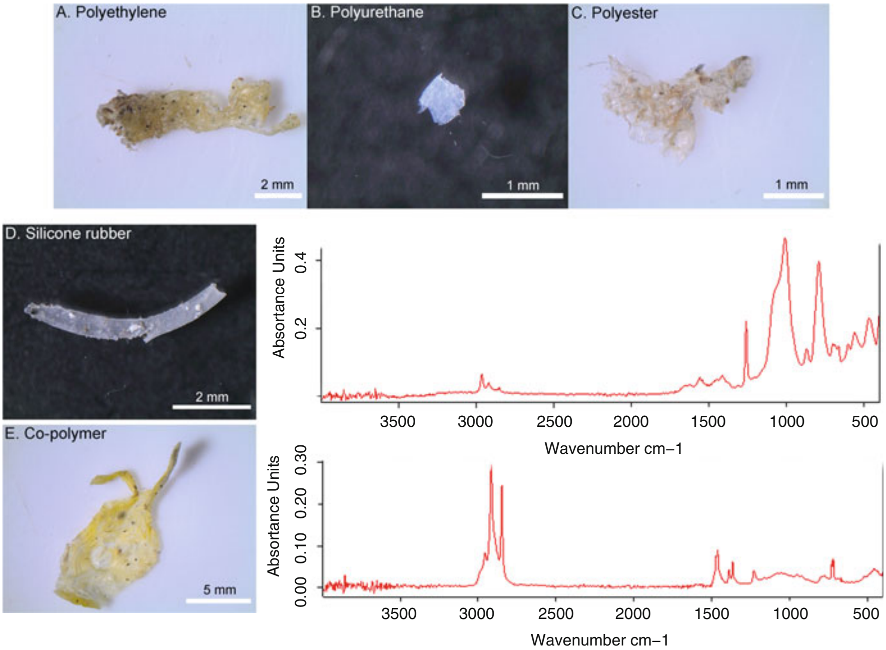

Fig. 3 Variety of plastic debris recovered from Nile perch and Nile tilapia. Images (**a**–**e**) are examples of the range of polymers isolated after NaOH digestion of the gastrointestinal tissue. In each case the identity of the polymer was confirmed by ATR-FTIR spectroscopy. Spectra attributed to silicone rubber (**d**) and polyethylene/polypropylene copolymer (**e**) debris are shown next to their respective plastic samples

Table 2 Polymers recovered from the gastrointestinal tracts of sampled fish and their common uses and potential source of plastic pollution in Lake Victoria

Polymer	Common uses and potential sources
PE/PP copolymer[a]	Packaging, carrier bags
Polyethylene	Carrier bags, food wrappers, beverage bottles
Polyester	Beverage bottles, textile (clothing, carpets, curtains)
Polyurethane	Insulation, sealants, packaging
Silicone rubber	Industrial sealants. O-rings, molds, food storage

[a]PE (polyethylene)/PP (polypropylene)

3.3 Plastics and MPs in Lake Victoria

Together these two cases provide compelling evidence that plastic debris in the Tanzanian waters of Lake Victoria is subject to degradation and the products of that breakdown are available for ingestion by resident piscine populations. While Ngupula et al. [16] found fishing to be the predominant source of debris, the identification of different polymers from the fish intestinal tracts suggests a wider range of inputs related to urban waste [17].

The consequence of plastic debris and MPs in the lake ecosystem requires further research. Other types of solid waste, such as those originating from paper production and agriculture, were found to interfere with the distribution of macroinvertebrate communities in the Kenyan waters of Lake Victoria [52]. Future investigations could also consider the trophic transfer of MPs through the freshwater food chain, particularly in the case of Nile perch which are known to feed on smaller fish (*haplochromine* cichlids) and gastropods, as well as any potential "vector effect" that facilitates the movement of adhered contaminants through the food chain [53]. These are important aspects to study primarily because the top predators in these food chains are the local residents that ultimately consume the fish.

Given the existing population density surrounding Lake Victoria and its estimated growth, the prevalence of plastic debris and subsequently MPs is also likely to increase. The reliance on the lake as a resource means that any potential impacts of MPs on the ecosystem and biota need to be researched, assessed, and, if possible, mitigated. However, research activities should not be confined only to Lake Victoria. A number of African freshwater bodies are just as likely or even more likely to be impacted by MP pollution. Potentially, the main message to be taken from these case studies is the relative simplicity by which they were accomplished. In particular, the purchase of fish from market and subsequent dissections required little specialist scientific equipment and could be replicated in other locations. In the following section, we consider the current challenges to MP research and mitigation in Africa and discuss future research needs.

4 Current Challenges and Future Research Needs

With only two case studies available to highlight plastic and MP pollution in African waters, the most obvious challenge and research need is the lack of data. More studies are urgently required to assess the extent of MP pollution in African freshwaters, as well as their sources and their fate. However, let us assume that this lack of data does not indicate that MPs are not present in the environment and that further research would describe their presence. In this case, the more immediate challenges may be how to mitigate MP pollution rather than just report it. We argue that effective waste management, increased public awareness, and political will are all necessary to avoid deleterious impacts. However, it is the combination of these factors rather than each one in isolation that is likely to affect change.

4.1 Current Challenges

4.1.1 Waste Management

Unlike most developed nations where plastic waste is often separated from other wastes prior to disposal [54], the management of solid wastes in many developing countries can be considered as problematic often due to inappropriate technology and infrastructure [55]. Thus while a significant proportion of plastics in developed countries are collected and recycled [6], in most African countries, even in the presence of reuse and/or recycling practices, effective plastic waste management often lacks a legal foundation [24]. This results in urban and industrial wastes in developing countries being sent to disposal sites or dumped as mixed bulks [56]. This type of dumping of refuse has been documented as a major cause of pollution in African waters and is a recognized source for MP pollution (e.g., Fig. 2b).

In order to improve waste management practices, sustainable approaches should be a priority. Examples of these approaches could include establishing permanent recycling stations or working with communities to promote recycling and change their perception of plastic from disposable single-use items. However, such approaches require time and effort, and moreover do necessarily have an impact on the current level of plastic waste in the inland water bodies. Following the characterization of plastic litter in Mongolia’s Lake Hovsgol, local plans to regulate waste management and reduce waste production were suggested [25]. Based on the analyses and observations made in the two case studies presented in this chapter, similar proposals could certainly be made for this affected area and potentially implemented in other areas, following appropriate initial data collection and analysis.

One methodology that has been proposed for quickly assessing the impact of waste in the environment is the rapid environmental assessment (REA). The method involves scoring the abundances of key indicator species and the magnitude of environmental pressures concurrently on the same logarithmic assessment scale [57]. High pressure scores coupled with decreases in biological abundances indicate that urgent action is mediated. REAs were used to assess potential impacts and threats in the coastal region of Kerkennah, Tunisia. Solid waste densities, including plastics, were ranked with high scores, indicating the need for action, but scores for other pressures and biological abundance decreases were not determined to be high enough for remediation actions to take place. In this example the authors suggested that beach rubbish and coastal debris should be cleaned up, but further action was not needed at the present time [57]. While the REA approach demands a certain level of taxonomic knowledge, this is not prohibitory for the involvement of “non-experts” as the focus is taxonomic breadth rather than depth (i.e., broadscale). In Kerkennah, the training of team members without specific taxonomic or technical expertise was achieved via a 1–2 h PowerPoint presentation followed by trial REAs. Following training, assessment at each site was typically conducted in approximately

1 h [57]. While REAs capture low-resolution data, they do provide a means of grading levels of management urgency and response. Moreover, the surveyors need not be experts and could be sourced from the local community within a program set by the municipality or regional government – although such action requires political will and public awareness (as discussed in the following sections). Thus REAs with criteria (pressures and species indicators) tailored for site-specific thresholds could become a valuable tool in determining which African freshwater locations require remediation from MP pollution.

4.1.2 Political Will and Governance

Most of African freshwater bodies are transboundary (see Table 1), and therefore their management requires cooperation and effective, coherent regional environmental policies [58]. However, the management of most African transboundary lakes and rivers ecosystems is largely compromised by conflicting political standings among the riparian countries [59]. A good example of this is Lake Victoria which is shared by Tanzania, Kenya, and Uganda. Its management has been challenging due to a lack of good cooperation and harmonized policies mainly following the collapse of East African Community of 1977. Despite its reformation, there are still country-specific political issues hindering the management of the lake. This is also the case for other African Great Lakes like Lake Tanganyika and Lake Malawi. However, when policies, conventions, and cooperations do occur, the major focus is often on how natural resources can be shared [60], rather than the control of pollutants. Thus, at an international level, the political will to combat issues like MP pollution is not strong and is equally problematic at the local level. In most African countries, MP pollution is not recognized as emergent issue of concern, although the efforts to levy, reduce, and ban the use of plastic bags [26, 27] would suggest that the plastic issue is not entirely ignored.

It is perhaps stereotypical to consider, but in many African nations, the challenges faced are greater than MP pollution – war, famine, literacy rate, infrastructure, clean drinking water, poverty, and corruption [61]. Moreover, most African countries have insufficient budgets from which to plan and execute governmental projects including research activities. A number of countries receive financial aid, and under these circumstances, and understandably, the study of MP pollution is not of the highest priority. Based on this, the current financial challenges of working with MPs in African waters may not be solved by local budgets but rather by bringing together different stakeholders (i.e., local community, local and national governments, NGOs, researchers), in order to first collect data, evaluate steps forward, and implement effective measure to halt MP pollution.

4.1.3 Public Awareness

The role of the general public through awareness and active involvement (i.e., citizen science) is discussed in detail elsewhere in this book, both with an historical overview and specifics related to MP pollution (see Syberg et al. this volume [62]). Briefly it could be suggested that in comparison to other environmental issues, the public has been invaluable in assessing the magnitude of plastics and MP pollution through volunteer beach cleanups and surveys that provide data for monitoring programmers, as well as carrying out the practical task of removing beach litter. In the USA most information regarding the abundance and distribution of beach debris has been derived from volunteer beach cleaning efforts [63], and such public involvement is also occurring elsewhere. Public collaboration with scientific research has taken place in a number of locations worldwide, for instance, the collection of marine litter in the Firth of Forth, Scotland [64], collection of beach debris along the coast of southeast Chile [65], and many volunteers mobilized for beach surveys in South Africa [66]. However, to the best of our knowledge, such public-involving initiatives have not been attempted in areas surrounding African freshwaters. Part of this problem may be, as has been discussed, a scarcity of information regarding the scale of potential MP pollution, which results in a lack of funding and a lack of awareness.

As discussed, funding for environmental issues may not be the highest priority in most African countries, but NGOs which could collaboratively work with various public sectors have paid little or no attention in raising public awareness in the issue of plastic waste management [67]. Similarly, the opportunities for 3Rs (reduce, reuse, and recycle) are not well explored and advocated in developing countries [68]. It has been suggested that improved education on the issues of waste management in developing countries, and the preparation and training of environmental professionals and technicians, could be the way forward. Some developing countries have reported positive effects from investing in education, such as citizens assuming responsibility and higher status of waste workers, which have resulted in cleaner cities [68]. Such programs would potentially have similar results in urbanized regions around African freshwaters, and the downstream effect of cleaner cities would be less urban waste from which to produce MPs. But as mentioned earlier in this section, the increase of awareness and education of the population must be coupled with an increase in effective waste management and ultimately coherent regional political action.

4.2 Future Research Needs

To discuss the future research needs, we revisit the themes of this chapter – presence, sources, and fate of MPs in African inland waters. As mentioned several times, there is a dearth of information regarding the prevalence of MPs within

Africa's freshwaters. Filling this knowledge gap must therefore be the highest priority and an absolute necessity to further understandings of sources and fate. The two studies described in detail in this chapter have been conducted in the same region and found that the sources of plastic (and MP) pollution were linked to urban refuse and fishing activities. This echoes the findings of studies in other freshwater areas, where type of plastic and MPs reflect the usages and anthropogenic inputs of the local populations [10, 13, 25]. The population of Mwanza is estimated to be 1.12 million people by 2020 (Table 1), and while not an insignificant number, this is by no means the largest urban center close to a freshwater body. We, therefore, suggest likely candidates for future research are locations with high population densities.

The River Nile flows through a number of heavily populated cities, most notably, Khartoum in Sudan (almost six million inhabitants estimated by 2020), Alexandria (5.23 million), and, of course, Cairo (20.57 million) (Fig. 1, Table 1). While MPs have not been described in the Nile, other pollutants (i.e., trace metals Cd, Cr, Cu, Fe, Hg, Mn, Pb, and Zn) were found in the abiotic compartments and the tissues of resident fish populations [18]. It is worth noting that MPs have been shown to adsorb trace metals in the environment [69, 70], and within the laboratory, polyethylene MPs were shown to alter the bioavailability and uptake of Ag to freshwater zebra fish [71]. The River Congo similarly flows through densely populated cities, notably Kinshasa (14.12 million inhabitants) and Brazzaville (2.21 million), and these waters would also be suspected of having MPs present. Elevated trace metal concentrations in Congo sediments were found in the vicinity of urban runoff and domestic and industrial wastewater discharge into the river basin [72]. It would seem obvious to expect MPs to be present alongside other pollutants of urban origin in both these rivers.

How to determine the prevalence of MPs requires thought, and there are various sampling techniques to assess MP abundances to consider: (1) shoreline combing, (2) sediment sampling, (3) water trawls, (4) observational surveys, and (5) biological sampling. In different locations, some may be more or less relevant based on practical (the availability of personnel and equipment) and economic factors (i.e., funding). In our study (Case Study II [17]), reporting the presence of MPs in Lake Victoria, biological sampling was considered to be the most suitable technique as it required little specialist field equipment (i.e., mantra trawls or trawl nets), and the laboratory apparatus required to digest gastrointestinal tracts is relatively common. Additionally, the study was inexpensive as fish were purchased from the local market and the research could be conducted within a short space of time. However, it is necessary to select suitable biological indictors. Nonselective feeders provide a better reflection of MPs in the environment [32, 36]. For instance, the omnivorous fish, Nile tilapia, was used in Lake Victoria, and water-filtering mussels (*Mytilus edulis*) and sediment-dwelling lugworms (*Arenicola marina*) have been shown to take up MPs from their respective environments [73]. Studies such as the one we conducted in Lake Victoria only present a "snapshot" of MP pollution, and longitudinal studies are required to describe temporal and spatial differences. Where possible, a combination of techniques may be more advisable particularly to present a complete picture of MPs in the environment. However, with the current lack of information, reporting the presence of MPs from any compartment of African freshwater systems would be a welcome addition to the literature.

As described by Wagner et al. [8], information on the fate of MPs in freshwaters is scarce, if not absent. Some common questions that need to be addressed in all freshwaters and are still outstanding in marine waters include (1) the behavior of MPs in environment – how they distribute and where they settle; (2) interactions with biota, such as rates of excretion, accumulation, and infiltration in tissue; (3) effects of MP exposure in order to determine environmental hazard; and (4) interaction between MPs and other pollutants, the so-called vector effect. Such considerations are as important in African freshwaters as elsewhere, but as in most locations, regional concerns are also noted. As degradation rates of MPs are influenced by the amount and strength of UV radiation [74], MPs in African freshwaters, largely located in the tropics, are likely to be degraded faster than in more temperate conditions as reactions, such as photolysis, thermo-oxidation, and photooxidation, are accelerated in strong UV light [74, 75]. Degradation rates for MPs under these conditions and how this affects the aforementioned questions of distribution, biotic interactions, interactions with waterborne chemicals, and vector interactions should be determined.

In order to prevent and mitigate deleterious effects, the challenges of MP pollution cannot be dealt with by solely focusing on their presence and impacts in the environment, but rather investigation of the entire chain from production to disposal is mandatory [76]. Thus questions of fate must be integrated into the requirement to report the presence and understand the sources. We recommend the following focus areas to assess the current state of MPs in African inland waters:

1. Establishing a more complete picture of MP pollution in African freshwaters with the prioritization of locations with dense urban populations
2. Environmental monitoring programs that encompass water, sediment, and biota sampling and that consider spatial and temporal distributions
3. Life cycle assessments of plastics that consider production through disposal and fate in the environment
4. Interactions between MPs and (a) environmental factors, (b) other pollutants, and (c) resident biota

5 Conclusions

Knowledge regarding the presence, sources, and fate of MPs in freshwaters is being gathered apace in different parts of the world, but this information is currently lacking in Africa. Owing to the human pressures that increased urbanization has placed on many inland rivers and lakes, in combination with ineffective waste management and a general lack of awareness (although there are some notable exceptions, e.g., plastic bag bans), the potential for MP pollution is great.

The question then becomes, not if MPs are present, but where and how to sample them. The marine and estuarine research conducted in South Africa provides a potential guide via beach combing, water and sediment collection, and biological sampling. However, such efforts may be difficult in the absence of personnel, apparatus, and, of course, funding. Thus, the study of Biginagwa et al. [16], exemplified in Case Study II, in which MPs were extracted and identified from suitable biological indicators that inhabit the urbanized catchment area is offered as a model for research in other areas that can be conducted in a cost- and time-effective manner.

The confirmation of MPs is only the first step, albeit necessary for further understanding of sources and fate. Mitigating the effects of MPs requires the coming together of numerous interested stakeholders, not least the local populations. In the place where our species first evolved, it now falls on the current generation to preserve Africa's freshwaters for the future.

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