Title

Microplastics in African ecosystems: Current knowledge, abundance, associated contaminants, techniques, and research needs

Journal

The Science of The Total Environment, 755(Pt 1)

ISSN

0048-9697

Authors

Alimi, Olubukola S
Fadare, Oluniyi O
Okoffo, Elvis D

Publication Date

2021-02-01

DOI

10.1016/j.scitotenv.2020.142422

Science of the Total Environment 755 (2021) 142422

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Microplastics in African ecosystems: Current knowledge, abundance, associated contaminants, techniques, and research needs

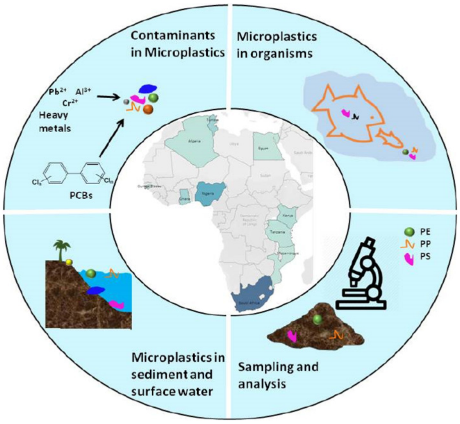
Olubukola S. Alimi [a,*], Oluniyi O. Fadare [b,c], Elvis D. Okoffo [d]

[a] Department of Chemical Engineering, McGill University, Montreal, Quebec H3A 0C5, Canada
[b] State Key Laboratory of Environmental Chemistry and Ecotoxicology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China
[c] College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China
[d] Queensland Alliance for Environmental Health Sciences (QAEHS), The University of Queensland, 20 Cornwall Street, Woolloongabba, QLD 4102, Australia

HIGHLIGHTS

- Limited studies exist on microplastic abundance in African ecosystem and organisms.
- High concentrations of hopanes, phthalates, zinc and sodium reported.
- Lack of effective sampling and analytical techniques revealed.
- No studies on microplastics in air and terrestrial environment.
- High levels of microplastics detected in fish from Egypt compared to other parts of the world.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 11 July 2020
Received in revised form 13 September 2020
Accepted 14 September 2020
Available online 21 September 2020

Editor: Damia Barcelo

Keywords:
Microplastic
Persistent organic pollutants
Metals
Africa
Plastic pollution
Effects and risks

ABSTRACT

Despite Africa ranking top in mismanaged plastic waste, there is insufficient data on the extent of microplastics and its interaction with other contaminants in its ecosystems. Microplastics pollution has been documented globally, however, specific data from the continent is crucial for accurate risk assessment and to drive policies. We critically reviewed 56 articles from 1987 to 2020 and provide an overview of the current knowledge of the abundance and distribution of microplastics and associated contaminants in African aquatic systems and organisms. Most of the studies were carried out in the marine environment and there is currently no available data on the abundance of microplastic pollution in the African terrestrial environment. We show that across all studies, 5–100% of all sampled aquatic organisms contained microplastics. Concerning high levels of microplastics were reported in fish from Egypt compared to other parts of Africa and the world. Across all persistent organic pollutants sampled in microplastics, hopanes and phthalates were present at high concentrations while sodium and zinc were high relative to other trace metals reported. The most frequently occurring plastics were polyethylene followed by polypropylene and polystyrene. We found that most of the studies relied on visual inspection (52%) > FTIR (38%) > Raman spectroscopy (5%) > Scanning electron microscopy (3%) > Differential scanning calorimetry (2%) for identifying microplastics. Major gaps in sampling and identification techniques which may have overestimated or underestimated the current levels were identified. We discuss other research priorities and recommend solutions to address these issues associated with microplastic pollution in Africa.

---

* Corresponding author.
E-mail address: olubukola.alimi@mail.mcgill.ca (O.S. Alimi).

https://doi.org/10.1016/j.scitotenv.2020.142422
0048-9697/© 2020 Elsevier B.V. All rights reserved.

Contents

1. Introduction

The global production rate of plastic has been increasing over the past six decades due to their durability, versatility, and cost-efficiency, reaching 360 million tons in 2018 (Plastics Europe, 2019). As a result of widespread usage combined with mismanagement, plastic wastes have become ubiquitous in the global environment. Over eight million tons of plastics have been reported to be dislodged annually into marine ecosystem (Naik et al., 2019). After release and exposure to mechanical abrasions, water, wind and sunlight, plastic debris in the environment will undergo degradation and fragmentation into smaller sized particles referred to as microplastics (MPs; fragments <5 mm) and nanoplastics (NPs; fragments <0.1 μm) (Alimi et al., 2018). The word "microplastics" is thought to be first used in Africa by Ryan and Moloneys in their research paper titled "Plastic and other artefacts on South African beaches: temporal trends in abundance and composition" in the year 1990 (Ryan and Moloney, 1990). The term however became widely accepted among researchers after Thompson's report in 2004 examined the abundance of microplastics in sediment from beaches, estuarine and subtidal around Plymouth, United Kingdom (Thompson et al., 2004). Since then, several studies have reported on the accumulation and contamination of micro/nanoplastics and the associated contaminants in surface waters, sediments, estuarine, and subtidal habitats as well as within aquatic and terrestrial organisms in every continent (Eerkes-Medrano et al., 2015; Free et al., 2014; Van Cauwenberghe et al., 2015). These studies have built increasing evidence that plastic particles can be ingested and accumulated, adsorb and desorb contaminants, and cause detrimental effects on organisms.

In the aquatic environments microplastics deleterious effects is enormous. Microplastics have been reported to adsorb persistent organic pollutants (POPs) from its surrounding environment which could be released upon ingestion and/or be a pathway for transfer into their tissues (Galloway et al., 2017; Rochman, 2015). Likewise, microplastics may contain chemical additives added during their manufacturing process and these toxic chemicals could leach from plastic particles leading to possible negative impacts to an organism (Alimi et al., 2018; Hermabessiere et al., 2017). The potential for microplastics to cause physical damage or injury to a variety of exposed aquatic and terrestrial organisms has been widely reported and includes adverse effect such as induction of oxidative stress, reduction of predatory performance, oxidative damage, effects on reproduction, reduction of feeding rate, mortality, decreased neurofunctional activity, development of pathologies, among others (de Sá et al., 2018; Fadare et al., 2019; Ribeiro et al., 2019). Consequently, this threatens the aquatic live, which constitute a major part of the food web and supports human existence. Plastic particles have been reported in food consumed by humans as well as drinking water, raising global concerns on food safety (Koelmans et al., 2019; Ribeiro et al., 2020). Given the importance of human safety and environmental protection, it is imperative to evaluate the occurrence and distribution of microplastics. Monitoring microplastics globally in various environmental compartments can provide basic empirical data to ascertain the level of pollution, areas with imminent threat, historical trends, and organisms' exposure (Shim et al., 2017). Although, the abundance and distribution of microplastics in most continents has been well documented, data on the extent of pollution is lacking in Africa.

Africa is the world's second largest and second-most populous continent with a population estimated as 1.3 billion, equivalent to 16.7% of the total world population (United-Nations, 2019). It is surrounded by the Mediterranean Sea to the north, the Isthmus of Suez and the Red Sea to the northeast, the Indian Ocean to the southeast and the Atlantic Ocean to the west (Sayre, 1999). Africa like other continents is not exempted from the current global challenges of plastic pollution. Between 1990 and 2007, from the available record of thirty-three countries out of fifty-four nations in Africa, the total estimated plastics consumption is approximately about 172 million tons of polymers and plastics valued at $285 billion (Babayemi et al., 2019). Even with this high rate of consumption, there exist poor waste management policies making the continent to rank tops globally in terms of mismanaged plastic. Compared to other continents, Africa has the least amount of freshwater bodies (9%) (Vallee et al., 2003) hence must be sustainably managed. Microplastic pollution therefore poses additional burdens on the African populace. Even though the first study reporting microplastics (no sized definition at that time) came from Africa, microplastics research in Africa is still in its infancy. Microplastic pollution awareness has increased in the last decade, however, very little is known about the occurrence, distribution, and fate of microplastics in different environmental compartments within the continent.

Despite available reviews on microplastics occurrence, fate in the environment and ecotoxicological impact (Hamid et al., 2018; Shim et al., 2018), there is no critical evaluation and synthesis of the current research related to microplastics detected in aquatic ecosystems from African countries. Thus, this paper presents the current knowledge about the abundance, distribution and fate of microplastics in different compartment across the Africa. We (i) offer a perspective on the abundance of microplastics in aquatic environment (sediments and surface waters) and organisms, (ii) synthesize and critically analyze studies that report the interaction of microplastics and persistent organic pollutants and metals (iii) evaluate current sampling and analytical methods and (iv) critically outline and discuss the knowledge gaps in microplastic research in Africa while suggesting future research directions.

2. Literature search

An exhaustive literature search was carried out using Scopus, google scholar databases and local journals for studies on microplastic in Africa from 1987 to June 2020. The purpose of the literature search was to identify all peer-reviewed articles and review papers on microplastics occurrence, abundance, transportation, fate and associated contaminants concentrations in different environmental medium from African countries. The keyword queries were "microplastics AND Africa", "microplastic AND Africa AND contaminants" and "plastic particles/debris AND Africa". The retrieved articles were sorted into years of publication, after which the abstracts were vetted to remove studies which were out of the scope of this review (mesoplastic and plastics). Altogether, a total of 56 articles were considered, comprehensively evaluated and recapitulated. Studies that fall into two or more broad categories were counted as separate studies which sums up to 71 studies. Three grey studies found on the international pellet watch database were included via google search. All reviewed studies were from 13 African countries namely, Algeria, Ghana, Nigeria, South Africa, Tanzania, Egypt, Tunisia, Guinea-Bissau, Mauritania, Equatorial Guinea, Mozambique, Ethiopia, and Kenya (Fig. 1a). The detailed description of all studies is provided in the Supporting information (S1). Fig. 1 shows an overview of the distribution of identified studies.

3. Current data on microplastics concentration in Africa

3.1. Abundance of microplastics in surface water and sediment

The proliferation and abundance of microplastics have been reported in surface waters and sediments in different continents across the world (Browne, 2015; Do Sul et al., 2014; Van Cauwenberghe et al., 2015; Woodall et al., 2014). The earliest study ever reported on the occurrence and distribution of microplastics in surface water in Africa dates back to 1988. This study sampled plastic particles at the sea surface in southwestern Cape Province of South Africa between August 1977 and August 1978 (Ryan, 1988). Likewise, Nel and Froneman conducted a study on surface water in South-eastern major bays of South Africa, (Nel and Froneman, 2015) but this was not until 27 years after the initial study on the continent (Nel and Froneman, 2015). Scanty studies have emanated from Africa to date on the distribution of plastic particles and their potential sources to the aquatic environments. This limits our understanding about the environmental risks associated with microplastic pollution on the continent. Based on the available literature to date, microplastics distribution in surface waters either from marine or freshwater source have been reported in five countries (about 9.3%) out of fifty-four countries on the continent (Fig. 1). No study has emerged from central African region to date, while South Africa is the only country from the southern part of Africa that has reported all the studies on microplastics distribution and abundance from the region. Hence, the comparison of microplastics abundance in different regions of the continent appears difficult due to limited studies and different measurement units used in reporting microplastics abundance and distribution. Nonetheless, current information presented in Tables 1 and 2 and Fig. 2 shows a summary of different studies conducted both in marine and freshwater systems. The particle size range reported in the studies under review were in the range of 0.0012–5 mm. In surface waters, the highest abundance of microplastics were from South-eastern bays of South Africa and Ox bow lake in Yenogoa, Nigeria having 1215 and 8369 particles/m^3 respectively. The two countries are among the highest producers of mismanaged plastic waste per capita in Africa (Jambeck et al., 2018). It is therefore not surprising that the highest microplastic abundance recorded on the continent was from these countries. However, it is noteworthy to state that the concentrations reported in Nigeria was sampled

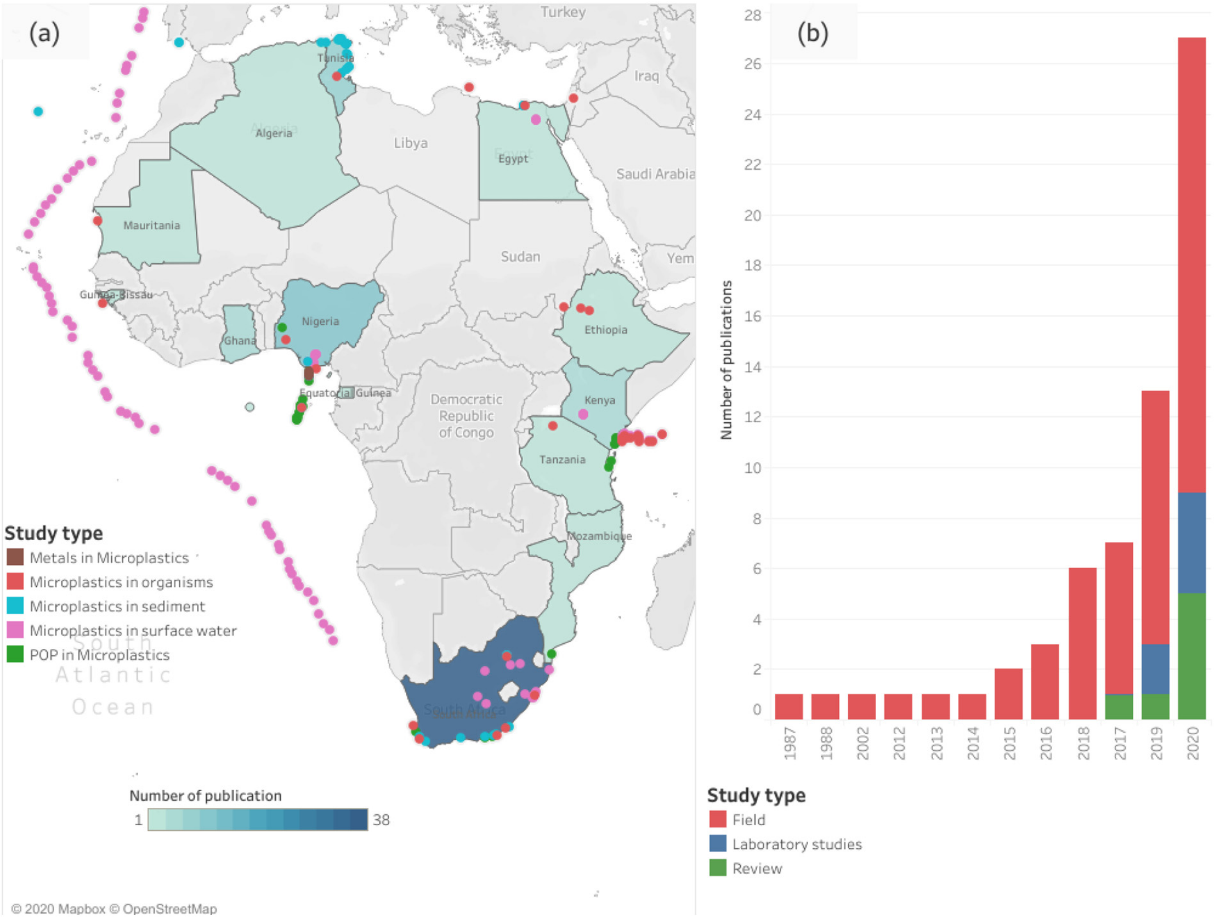


Fig. 1. (a) Spatial distribution of microplastic publications across Africa (b) Distribution of yearly publication in Africa. POP - persistent organic pollutants.

Table 1
Abundance of microplastics in surface waters across Africa.

Country	Location	Environmental compartment	Microplastics abundance	Particle sizes (mm)	Reference
Ghana	Sakumo II	Marine surface water	0.09 p. mL^{-1}	0.1–5	(Gbogbo et al., 2020)
Kenya	Naivasha	Lake surface water	0.407 ± 0.135 p. m^{-2};	1–5	(Migwi et al., 2020)
Nigeria	Yenogoa	Lake surface water	1004–8329 p. m^{-3} (dry season); 201–8369 p. m^{-3} (wet season)	0.02–0.5	(Oni et al., 2020)
South Africa	Braamfontein Spruit, Johannesburg	Stream surface water	705 p. m^{-3}	0.053–4	(Dahms et al., 2020)
South Africa	Orange-vaal	River surface water	2.3 ± 7.2 p. L^{-1} (wet season); 1.4 ± 2.6 p. L^{-1} (dry season)	0.025–1	(Weideman et al., 2019)
Nigeria	Niger Delta	River surface water	–	<0.3	(Briggs et al., 2019)
Nigeria	South eastern coast	River surface water	440–1556 p. L^{-1}	–	(Enyoh et al., 2019)
Egypt	Eastern Harbour	Seawater	33–174 p. 100 g^{-1} dw	0.5–5	(Shabaka et al., 2019)
South Africa	KwaZulu-Natal	Marine surface water	5.54 ± 3.26 p/100 m^2 (winter) 2.96 ± 2.94 p/100 m^2 (summer)	0.25–1	(Naidoo and Glassom, 2019)
Kenya	Central Kenya	Surface seawater	110 p. m^{-3}	0.25–2.4	(Kosore et al., 2018)
South Africa	Cape town	Bay of Biscay surface water	1.15 ± 1.45 p. m^{-3} Range: 0–8.5 p. m^{-3}	0.25–5	(La Daana et al., 2017)
South Africa	East and south coast	Marine surface water	413.3 ± 77.53–1200 ± 133.2 p. m^{-3}	0.63–5	(Nel et al., 2017)
South Africa	South-eastern major bays	surf-zone water	257.9 ± 53.36–1215 ± 276.7 p. m^{-2}	0.080–5	(Nel and Froneman, 2015)
South Africa	Durban	Seawater	70.3 ± 119.3 p/10,000 L	0.02–1	(Naidoo et al., 2015)
South Africa	South western cape province	Marine surface water	3640 p. km^{-2}	–	(Ryan, 1988)

during the rainy season and microplastic abundance has been observed to be higher in surface waters during the rainy season than the dry season. For instance, 15,560 particles/m^3 was reported in River Nakdong, South Korea during the rainy season in comparison to 1410 particles/m^3 recorded during the dry season (Tsang et al., 2017). A similar trend during the rainy season was reported in a parallel study carried out by Weideman et al., 2019 in Orange-vaal river, South Africa (Weideman et al., 2019). Also, an increase in microplastic abundance up to two-folds was reported by Nadioo and Glassom, during the winter season in comparison to summer in marine water from coastlines of South Africa (Naidoo and Glassom, 2019). This suggests a significant relationship between microplastics abundance/distribution and seasonal variation as this plays a crucial role in the transport of plastic particles from land-based sources into the aquatic system. In addition, anthropogenic and industrial activities around and within these regions have been identified as the major contributor (Naidoo and Glassom, 2019). On the other hand, a report from Kenya reported the lowest microplastic abundance from Naivasha lake surface water having an average value of 0.407 ± 0.135 particles/m^3, comprising mainly of polypropylene, polyethylene, and polyester.

Sediments are known to be a huge sink for microplastic in the aquatic environment due to the higher density of most plastic particles in water

Table 2
Abundance of microplastics in sediments across Africa.

Country	Location	Environmental compartment	Microplastics abundance	Size (mm)	Reference
South Africa	Mutoti and Budeli	Marine sediment	120–6417 p. kg^{-1} dw (hot-dry season); 5–94 p. kg^{-1} dw (hot-wet season)	0.5–5	(Mbedzi et al., 2020a)
Ethiopia	Lake Ziway	Freshwater	6.3–115.9 p. kg^{-1} dw	0.15–5	(Merga et al., 2020)
Tunisia	southern Mediterranean	Marine sediment	129–606 p. kg^{-1} dw	0.0012–1	(Missawi et al., 2020)
Tunisia	Gulf of Annaba	Marine sediment	182.66 ± 27.32–649.33 ± 184.02 p. kg^{-1} dw	0.81–2.16	(Tata et al., 2020)
Tunisia	Bizerte	Freshwater sediment	2340 ± 227.15–6920 ± 395.98 p. kg^{-1} dw	0.2–5	(Toumi et al., 2019)
Ghana	Sakumo II	Marine sediment	1.85 p. g^{-1}	0.1–5	(Gbogbo et al., 2020)
Nigeria	Yenogoa	Lake sediment	1004–8329 p. m^{-3} (dry season); 201–8369 p. m^{-3} (wet season)	0.02–0.5	(Oni et al., 2020)
South Africa	Braamfontein Spruit, Johannesburg	Stream sediment	166.8 p. kg^{-1} dw	0.053–4	(Dahms et al., 2020)
Tunisia	Sidi Mansour, Sfax-Tunisia	Marine sediment	2932 ± 63 p. m^{-2};	0.1–5	Chouchene et al., 2019
Nigeria	Alpha, Oniru, Eleko, Lekki	Beach sediment	121 ± 38–170 ± 21 p	–	(Ilechukwu et al., 2019)
Egypt	Eastern harbour	Marine sediment	33–174 p. 100 g^{-1} dw	0.5–5	(Shabaka et al., 2019)
South Africa	South-east coast	Beach sediment	80–87 p. dm^{-3};	0.04	(de Villiers, 2019)
South Africa	South and east coast	Riverbank sediment	0–567 p. dm^{-3}	–	(de Villiers, 2018)
South Africa	Eastern Cape Town	River sediment	13.3–563.8 p. kg^{-1}; 160.1 ± 139.5 p. kg^{-1}	–	(Nel et al., 2018)
Tunisia	South/North Lake of Tunis	Sediment	316.03 ± 123 p. kg^{-1} dw	0.1–5	(Abidli et al., 2018)
Tunisia	Menzel Abderrahmane, Carrier bay, Menzel Jemil, Channel of Bizerte	Lagoon sediment	7960 ± 6840 p. kg^{-1} dw	0.3–5	(Abidli et al., 2017)
Mauritania/Guinea-Bissau	Banc d'Arguin; Bijagos archipelago	Marine sediment	0.7 ± 0.65–6.7 ± 2.40 p. mL^{-1}	0.5–1	(Lourenço et al., 2017)
South Africa	Durban Bay	Marine sediment	100–1900 p. kg^{-1} dw	0.315–5	(Matsuguma et al., 2017)
South Africa	East and south coast	Marine sediment	86.67 ± 48.68–754.7 ± 393 p. m^{-2}	0.63–5	(Nel et al., 2017)
South Africa	South-eastern major bays	Beach sediment	688.9 ± 348.2–3308 ± 1449 p. m^{-2}	0.065–5	(Nel and Froneman, 2015)
South Africa	Durban	Marine sediment	749 ± 129.7 p/500 mL	0.02–1	(Naidoo et al., 2015)
Algeria	Southern west Mediterranean coast	Azew gulf sediment	–	1–5	(Bouchentouf and Driss, 2013)

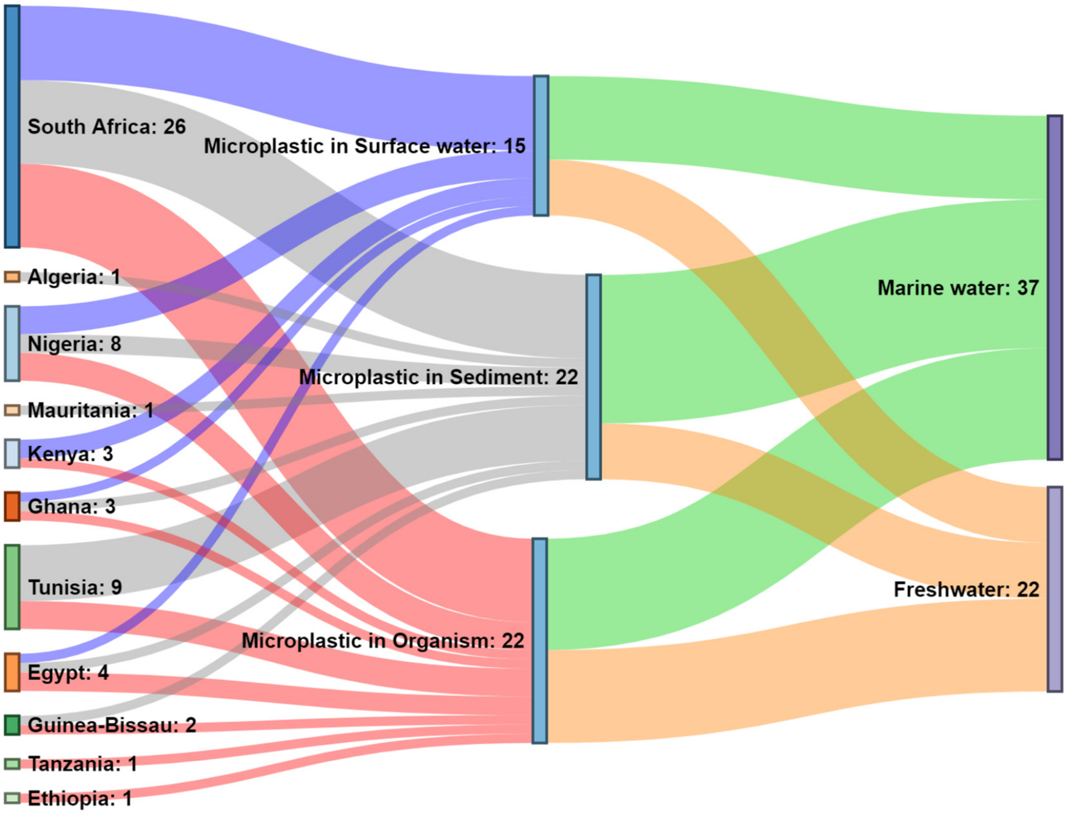


Fig. 2. Distribution of publications reporting the abundance of microplastics in various environmental compartments. The width of each node/band is proportional to the number of studies for that node. First layer; country, second layer: type of study, third layer: environmental system.

(Woodall et al., 2014). Microplastics distribution in sediments reported across the continent ranged from 5 to 18,000 particles/kg dry weight, with the highest abundance recorded in lagoon sediments in Tunisia comprising of majorly fibers and fragments (Table 2). This study is one of the highest microplastic abundances in sediments reported so far globally and it was attributed to heavy marine and industrial activities around this region, being ranked second in terms of seafood product exports (Abidli et al., 2017). Sampling sites where high concentrations have been reported include Beibu Gulf and the coastline of China sea (8714 particles/kg) (Qiu et al., 2015), Canadian Lake Ontario nearshore (20–27,830 particles/kg) (Ballent et al., 2016), and in the Kachelotplate (62,100 particles/kg) (Liebezeit and Dubaish, 2012).

Spatio-temporal distribution of microplastics in sediments was reported from four studies in all the studies reviewed. Three of the studies observed an increase in microplastics abundance in sediments during the rainy/wet/winter season while one of the study reported the opposite (Mbedzi et al., 2020a). Environmental factors such as hydrodynamic may be responsible for this disparity in observation reported. Nonetheless, more field studies are required in this area of research for valid assertion. In all studies, we see that the extent of microplastic pollution in central Africa in unknown.

On the global scale, a review on Asia by Hamid et al.,2018 reported the lowest concentration as 0.0034 ± 0.0258 and highest as 6390 ± 862.7 particle/m^3 from Taihu and Sha lake of China respectively in surface water. Similarly, in Europe, 0.002 ± 0.001 to 6980 particle/m^3 were reported from Aveiro and Algarve in Portugal respectively (Hamid et al., 2018). Furthermore, the microplastics abundance in sediments from Europe, reported in particle/kg dry weight, ranged between 0 and 7 particle/kg in the Baltic coast of Germany and 672–2175 particle/kg in the lagoon of Venice in Italy. In North America, the lowest and highest microplastic concentration in sediments ranged between 43 and 56 particle/kg and 306–443 particle/kg in the Dry Tortugas National park and Virgins Island National Park in USA respectively. Comparing these global reviews and the present study, the high abundance of microplastic in surface water and sediments reported in Africa, was found to be comparable with some reported by Hamid et al., 2018 in America, Europe and Asia (Hamid et al., 2018). On the contrary, a review by Shim et al., 2018 found higher levels in Asia, North America and Europe compared to other continents (Shim et al., 2018) as well as this present study in Africa. Several factors may be attributed to some of the high levels of microplastic observed in Africa. This may be attributed to the lack of effective waste management system even though plastics are more consumed in Asia and Europe than Africa. Another reason may be attributed to overestimation of microplastic due to inappropriate analytical techniques (discussed in Section 7). Notwithstanding, more empirical data is required for proper risk assessment.

3.2. Abundance of microplastics in aquatic organisms

The presence of microplastics in aquatic organisms is often used as an indicator for microplastic pollution and potential to enter the foodweb. In the African ecosystem, the evidence of microplastics accumulation in aquatic organisms have been shown across 22 studies. Although direct comparison across studies is difficult because of the various units of measurement used, we attempt to provide a comprehensive overview to observe trends. Table 3 presents a summary of field studies that assess the abundance of microplastics in marine and freshwater organisms with 50% of all studies published in year 2020. The target parts of the organism for assessing microplastics across all studies ranged from the gastrointestinal tract, faeces and whole organism. The highest prevalence of microplastics (100%) was found in worms (*Gunnarea gaimardi*) and gastropods (*Lanistes varicus*) in coastlines of South Africa and Nigeria, respectively. Some studies recorded high concentrations of microplastics in organisms, irrespective of measurement units. In terms of wet weight, Akindele et al., 2020 reported as high as 291 ± 26.55 particles per gram wet weight from 3 insect species, with different feeding guilds in two Gulf of Guinea tributaries in Nigeria (Akindele et al., 2020). Although the source of the high levels of microplastic could not be accounted for, the sampled sites in Nigeria are heavily populated zones (Akindele et al., 2020). Abidli et al., 2019 reported high concentration of microplastics in mussels from Tunisia (1031 ± 355.69 particles/kg) (Abidli et al., 2019). The authors had previously shown that the sediment in same location was a hotspot for microplastics (7960 ± 6840 particles/kg dry weight, Table 2) (Abidli et al., 2017). Interestingly, Shabaka et al., 2020 recovered 7000 particles/fish from the Mediterranean coast of Egypt which is the current highest amount of microplastics ever recovered from aquatic organisms globally (Shabaka et al., 2020). Global reviews have reported a maximum concentration of 8.99 particles/organism (Hamid et al., 2018), 0.21–19 particles/organism (Herrera et al., 2019) and 57.2 particles/organism (Rezania et al., 2018). These high levels in Africa (Egypt) compared to the rest of the world is concerning and calls for urgent attention.

Most studies were focused on organisms from marine environments compared to freshwaters (Fig. 2). Freshwater systems are a major pathway for the transport of microplastics from the terrestrial to marine environment. Africa contains some of the largest freshwater bodies in the world which supports the water and food needs of most of the populace, yet, the extent of microplastic pollution in these systems are not known. Interestingly, a recent study by Khan

Table 3
Abundance of microplastics in aquatic organisms across Africa.

Country	Location	Compartment	Organism	Microplastics abundance (MPs/organism * = MPs/g dw ** = MPs/g ww $^{\#}$ = MPs/mL)	Occurrence	Size (mm)	Reference
Egypt	Eastern Harbour	Marine	Fish (8 species)	28 ± 21–7527 ± 9551	–	< 2	(Shabaka et al., 2020)
Nigeria	Osun river	Freshwater	Insect (*L. viridis* *Siphlonurus sp.* *Chironomus sp.*)	43.29 ± 43.29** 62.36 ± 3.53** 291.76 ± 26.55**	–	< 0.02	(Akindele et al., 2020)
Ethopia	Lake Ziway	Freshwater	Fish (*4 species*)	4.4 ± 3.6 1.1–56.3 mg/kg ww	35%	0.1–5 (70%) 5–25 (<25%)	(Merga et al., 2020)
Tunisia	Tunisia	Marine	Fish (*Serranus scriba*)	3.63 ± 0.2–6.11 ± 0.2* 1.78 ± 0.26–6.03 ± 0.47*	–	0.00045–0.003	(Zitouni et al., 2020)
South Africa	Johannesburg	*Freshwater (benthic)*	*Chironomus sp.*	19.8–96.7**	100%		(Dahms et al., 2020)
Tunisia	Southern Mediterranean	Marine	Seaworm	0.5 ± 0.1–3.7 ± 0.2*	–	0.0012–5	(Missawi et al., 2020)
South Africa	Cape Town	*Marine*	Mussels (*Mytilus galloprovincialis*, *Choromytilus meridionalis*, *Aulacomya ater*)	2.33 ± 0.2* 4.27 ± 0.5	98%	0.05–1	(Sparks, 2020)
South Africa	Agulhas Bank	Marine	Fish (7 species)	3.72 ± 2.73	87%	< 5	(Sparks and Immelman, 2020)
Nigeria	Eleyele Lake	Freshwater	Fish (8 species)	1–34	69.70%	0.126–1.53	(Adeogun et al., 2020)
South Africa	Mangrove	Marine	Juvenile Fish (*O. mossambicus* *O. mossambicus* *T. jarbua* *Mugil sp.* *Mugil sp.* *A. dussumieri*)	0.41 ± 0.57 0.59 ± 0.73 0.66 ± 0.81 1.14 ± 1.25 1.00 ± 1.46 0.93 ± 0.75	38% 45% 48% 59% 55% 69%	0.1–4.8	(Naidoo et al., 2020)
Egypt	Nile River	Freshwater	Fish (Nile Tilapia) Fish (Catfish)	7.5 ± 4.9 4.7 ± 1.7	75.90% 78.60%	0.25–5	(Khan et al., 2020)
Ghana	Eastern Central Atlantic Ocean	Marine	*Sardinella maderensis* *D. angolensis* *Sardinella aurita*	32 ± 2.7 25.7 ± 1.6 40 ± 3.8	41% 33% 26%	–	(Adika et al., 2020)
Nigeria	Osun river	Freshwater	Gastropod (*Lanistes varicus* *Melanoides tuberculata*)	3.8 ± 0.83 1.7 ± 0.42	100% 80%	–	(Akindele et al., 2019)
Tunisia	Lagoon of Bizerte	Freshwater	Mollusc (6 species)	1031.1 ± 355.69/kg ww		0.05–5	(Abidli et al., 2019)
South Africa	Southeast coastline	Marine	Polychaete (Gunnarea gaimardi)	0.275 ± 0.215*	100%	–	(Nel and Froneman, 2018)
South Africa	Barberspan Nature Reserve	Freshwater	Duck faeces Duck feathers	– –	5% 10%	< 1	(Reynolds and Ryan, 2018)
Kenya	Central Kenya	Marine	Zooplaankton (*chaetognatha*, *copepoda*, *amphipoda*, *fish larvae*)	0.16–0.46		0.01–1.6	(Kosore et al., 2018)
South Africa	Bloukrans River	Freshwater	Blood worm (*Chironomus spp.*)	0.37 ± 0.44* 1.12 ± 1.19*	75% summer 98% winter	–	(Nel et al., 2018)
Guinea-Bissau	Bijagos	Beach Sediment	Shore bird	0.1 ± 0.26–2.09 ± 3.15$^{\#}$	26%	–	(Lourenço et al., 2017)
Tanzania	South Shore Lake Victoria	Freshwater	Nile Perch (*Lates niloticus*) Nile Tilapia (*Oreochromis niloticus*)	– –	20% 20%	–	(Biginagwa et al., 2016)
South Africa	Durban Harbour	Estuarine	Fish (*Mugil cephalus*)	3.8 ± 4.7	73%	–	(Naidoo et al., 2016)
South Africa	Southwestern Cape	–	Seabirds (21 species)	–	60%	–	(Ryan, 1987)

et al., 2020 documented the first evidence of microplastic in the longest River in the world, River Nile (Khan et al., 2020). This river is one of the top ten rivers highlighted to be major culprits of plastic pollution to the oceans (Schmidt et al., 2017). The authors sampled the gastrointestinal tracts of two fish species with two different feeding habits (carnivore and herbivore) and found 75% of the samples to be contaminated with at least one plastic particle. The mean concentration recorded was 7.5 ± 4.9 and 4.7 ± 1.47 microplastic/fish for Nile tilapia and catfish respectively (Khan et al., 2020).

The type of plastics found in organisms across all studies vary significantly. A significant amount of studies report very high concentrations of fibers. A recent study found 87% of 7 fish species to contain 95% microfibers out of all microplastics in South Africa. While these levels of microfibers are considerably high, the authors did not provide the composition of the fibers (Sparks and Immelman, 2020). Some authors reported high levels of fibers (67%) in microplastics collected from mussels in South Africa (Sparks, 2020). Abdili et al., 2019 found that 97% of microplastics in mussel recovered from Tunisia were fibers (Abidli et al., 2019). The work of Akindele et al., 2020 also showed that fibers dominated the plastic types recovered from insects in Nigeria (Akindele et al., 2020). Microfibers have been widely reported as among the dominant plastic type found in most aquatic biota, (Rochman et al., 2015) hence this high prevalence of microfibers are not surprising. A wide variety of polymer types were recovered from organism under review compared to those recovered from surface waters and sediments (Fig. 3). Polyethylene is the most occurring plastic type found in all organisms followed by polypropylene. This order is also observed in surface waters. A recent study show that these two polymers are also the most frequently occurring polymers in freshwater systems (Koelmans et al., 2019). This correlates with the global plastic demand which is polyethylene > polypropylene (Geyer et al., 2017). Overall, few studies have investigated the accumulation of microplastic in organisms in African ecosystems. Hence, more studies are needed to fully understand the extent of pollution for proper risk assessment.

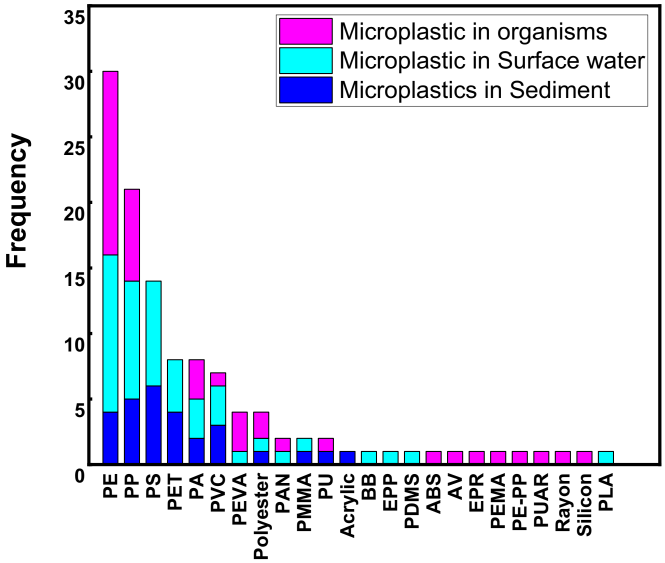


Fig. 3. The distribution of plastics types recovered from all studies across Africa. polyethylene – PE, polystyrene – PS, polyethylene terephthalate - PET, polypropylene - PP, polyvinyl chloride – PVC, Polyamide (Nylon) – PA, Polymethyl methacrylate – PMMA, Polyethylene-polypropylene copolymer – PE-PP CPM, Polyacrylates – PAK, Polyacrylonitrile – PAN, Polyester – PES, Polyurethane – PU, Polydimethylsiloxane – PDMS, Poly (lauryl acylate) – PLA, Butylbranham – BB, Ethylene propylene – EPP. Alkyd-varnish – AV. Summary of plastic types for all studies are presented in Tables S6–S8.

4. Abundance of persistent organic pollutants and metals in microplastics across Africa

Several studies have shown that microplastic can act as sources and sinks for persistent organic pollutants (POPs) as well as inorganic contaminants (Alimi et al., 2018). Source contaminants are intentionally added ingredients (e.g. additives, phthalates, etc.) during the manufacturing process to improve the physiochemical or mechanical property of the plastic while sink contaminants are those that adsorb unto the microplastic during its lifetime in the environment (e.g. polychlorinated biphenyls, PCBs and dichlorodiphenyltrichloroethane, DDTs). Some contaminants can be both source and sink contaminants (e.g. phthalates). Due to their hydrophobic nature and high specific surface area, microplastic readily adsorb organic contaminants, sometimes accumulating several orders of magnitude levels higher than the background environment. Hence, this area of research is of interest to the scientific community because these contaminants which have been shown to cause adverse health defects on their own, can leach from microplastic into other environmental compartments, bioaccumulate in aquatic organisms and potentially get transferred through the food web.

Although, programs (e.g. The Stockholm convention) have been put in place globally to regulate and reduce the release of POPs into the environment, increasingly high concentrations of POPs are still being detected globally. POPs have been well reported in the marine and terrestrial environments and organisms in Africa (Bruce-Vanderpuije et al., 2019; Hosoda et al., 2014). Emerging studies are now documenting the levels of these contaminants in microplastics. Since there is limited information on the levels of contaminants in microplastics in freshwater systems, the focus of this section is on the marine environment. The level of these pollutants is usually assessed by analyzing discolored microplastic pellets collected from coastal beaches. In addition to studies carried out by research institutes, International Pellet Watch, a volunteer-based organization is using a citizen science approach to document the global concentrations of organic pollutants such as PCBs, polycyclic aromatic hydrocarbons (PAH)s, hexachlorocyclohexane (HCH), DDTs, chloranes and hopanes (Takada, 2006). Fig. 4 presents a current overview of pollutants that have been detected in microplastics from different studies in Africa. A total of 6 classes of organic contaminants (Fig. 3a) were identified from several sites in 7 countries (Fig. S1). It is important to note that, due to the variability observed even in same environmental sample, most studies report the median concentration (circle symbol) rather than the mean (cross symbol). It can be observed that all classes of POPs fall within similar concentration ranges across all studies. For example, PCBs, HCH, DDT generally fall between 0.5 and 100 ng/g while phthalates, PAH and hopanes are >100 ng/g (Fig. 4a). Irrespective of the location or country, the levels of hopanes recorded were high and ranged from 1699 to 39,301 ng/g. This concentration range is in the same order of magnitude as those reported in Netherland (50571), USA (12301), Portugal (70580) and United Kingdom (77084) (Yeo et al., 2017). From Fig. 4a, the levels of phthalates in Nigeria - although reported as mean concentration - is high (210 ng/g – 50,030 ng/g) in all 6 sampling sites (Benson and Fred-Ahmadu, 2020). There are very few studies globally that examine the levels of phthalates in microplastics and this is one of the first study to show its concentration in microplastics in Africa. Phthalates are plasticizers added during the manufacture of plastics (e.g. PVC) to enhance their flexibility, durability and transparency. In a bid to delineate if the phthalates were inherent in the pellets or came from the surrounding environment, the authors quantified the level of phthalates from pristine pellets to range from 200 to 20,000 ng/g, indicating that the phthalates recovered from the microplastics might have originated from the pristine pellets rather than solely the surrounding environment. Hosoda et al., 2014 sampled plastic pellets from 11 beaches in Ghana and found 13 PCB congeners with a total concentration ranging from 1 to 69 ng/g (Hosoda et al., 2014). The concentration

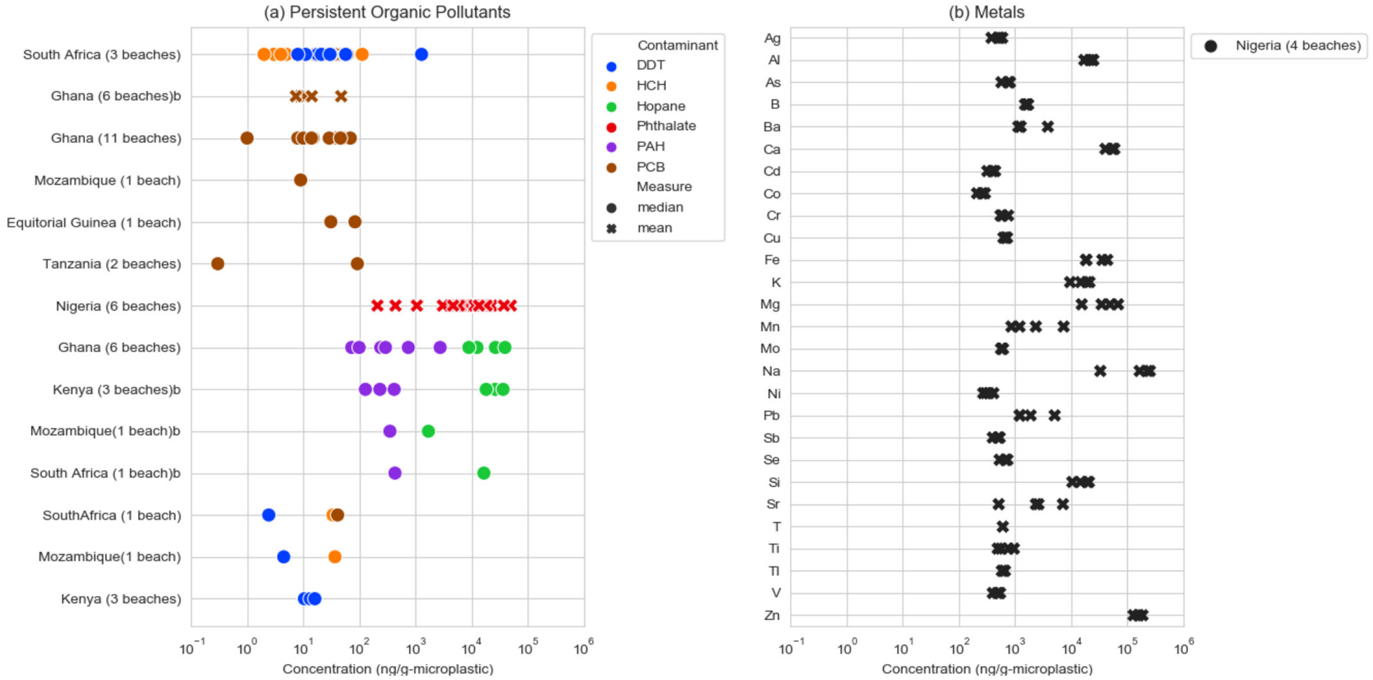


Fig. 4. An overview of contaminants associated with microplastics in coastlines across Africa. (a) Persistent organic pollutants (b) Metals. Details of all references are provided in the supporting information (Table S3 & Fig. S1). Ag = silver, Al = aluminum, As = arsenium, B = boron, Ba = barium, Ca = calcium, Cd = cadmium, Co = cobalt, Cr = chromium, Cu = copper, Fe = iron, K = potassium, Mg = magnesium, Mn = manganese, Ni = Nickel, Pb = lead, Sb = antimony, Sn = tin, Sr = strontium, Ti = Titanium, V = vanadium, Zn = zinc. DDT-dichlorodiphenyltrichloroethane, HCH-hexachlorocyclohexane, PAH-polycyclic aromatic hydrocarbons, PCB-polychlorinated biphenyls.

of PCBs in the background sediments was 0.57–32.2 ng/g suggesting that the PCBs might have originated from other local sources or that the microplastics have a stronger affinity for the contaminants compared to the background sediments. The total range of PCB's sampled from Ghana, Mozambique, Equatorial Guinea, South Africa and Tanzania is generally in same/lower order of magnitude with those recorded in other parts of the world. For example, one study in Japan recorded a high range (28–2300 ng/g) of PCBs (18 congeners) in PE and PP beached pellets from 47 locations (Endo et al., 2005). Another study in Brazil found up to 7550 ng/g PCB from 41 beaches (Taniguchi et al., 2016).

While these studies have provided the baseline concentration of POPs in microplastics in Africa, it is unclear how these concentrations vary seasonally or from year to year. A study by Ryan et al., 2012 reported the long-term variation of PCBs, HCH and DDT from 3 South African beaches over a 15-year span (Ryan et al., 2012). They showed that the concentration of these POPs generally decreased over the years studied.

Metals have also been shown to interact with microplastics in the environment and is increasingly been studied worldwide. A lot of laboratory studies have shown the potential for both pristine and degraded microplastics to adsorb high levels of trace metals (Alimi et al., 2018; Yang et al., 2019). In the field, when microplastics degrade, they become oxidized thereby providing more favorable sites for the accumulation of trace metals. A recent first study reported the distribution and abundance of 27 metals from pellets sampled in the Gulf of Guinea along the Nigerian coast from 4 beaches (Fred-Ahmadu et al., 2020). The microplastics sampled and extracted were identified as PS, PE and PP. In general, they found that the mean concentration of all 27 trace metals ranged from 210 to 251, 910 ng/g. Among all trace metals investigated, calcium; Ca (40,720–58,610 ng/g), magnesium; Mg (15,390–68,200), iron, Fe (18,240–43,830 ng/g), aluminum; Al (17,100–24, 810 ng/g), sodium; Na (32,970–251, 910 ng/g) and zinc; Zn (128,660–186, 290 ng/g) were notably higher than others (Fred-Ahmadu et al., 2020). The source is unclear as the background levels in sediments were not reported. Nevertheless, the location of the four sampling sites, Lagos, Nigeria is highly populated and has a lot of industrial activities. The levels of Ca, Mg, Na and Fe may not be surprising as they could have been accumulated from the surrounding seawater. It is important to note that some metals are added as additive during the manufacturing process (Hong et al., 2018). However, the levels of Al and Zn are concerning. These levels are in same or higher order of magnitude compared to those reported in other parts of the world. One study reported 8000 ng/g Zn, 45,000 ng/g Al and 228,000 ng/g Fe in Brazil (Vedolin et al., 2018).

It is important to note that most of these studies do not report the type and size of microplastics which prevents a holistic assessment. To properly assess the risks associated with POPs and metals in microplastics, more studies are needed to fully understand the spatial distribution of these contaminants in the environment. Additionally, it is important to have a unified measure of reporting for better comparison across studies.

5. Ecotoxicological studies of microplastics under laboratory conditions

Despite the ubiquity of plastic debris in the African continent, only a few laboratory studies have been carried out to elucidate the possible effects of microplastics on aquatic organisms. Six (6) of these studies (Table S2) evaluated the exposure of fish species while 1 study used sea cucumber all of which are native to the African ecosystem. Several endpoints such as mortality, neurotoxicity, physical effects, oxidative stress, blood/haemolymph effects etc. are monitored in these studies. A recent study exposed African freshwater catfish to PVC microplastics via their diet (Iheanacho and Odo, 2020a; Iheanacho and Odo, 2020b). They found that the plastic particles induced oxidative stress, neurotoxicity and lipid peroxidation which significantly affected the physiological state of the fish. Mbedzi et al., 2020 examined the functional response of African Tilapia fish to polyethylene microplastics and showed no negative effect was observed (Mbedzi et al., 2020b). In one of the first studies to investigate sea cucumbers, *H. cinerascens* were exposed to polyester microfibers and low-density polyethylene fragments (Iwalaye et al., 2020). They studied the uptake route via feeding and respiratory trees and found 100% of the samples contained microfibers attached to their respiratory tree and coelomic fluid. Sea cucumber are known to be non-selective feeders and are an important delicacy to some people, hence, more attention is needed on their interaction with microplastics in the environment. It is evident that laboratory studies investigating the effects of microplastics to organisms in the African ecosystem is still in its infancy. Hence, more studies are needed to assess the potential risks associated with these pollutants.

6. Sampling for microplastics analysis

Sampling techniques used in the collection of environmental samples for microplastics analysis, especially in the aquatic system is vital to the overall estimation of its abundance. Although, there is no agreement or consensus on sampling, due to the present limitation in the detection techniques of microplastics in the water column, large sample volume is required for surface water (Browne, 2015). Different sampling methods have been employed across the globe such as trawling with varying nets of plankton, neuston, and more effective methods are being developed like direct fractionated pressure filtering of large volume of water (>1 m^3) through a filter cascade. Other known sampling techniques are bulk sampling with filtration, screening continuous plankton recorder, direct in-situ filtration, ex-situ filtration and screening (Browne, 2015). The selection of any of these methods will depend on factors such as the sampling source, volume to be sampled, depth and the available equipment. In the studies under review, the majority employed trawling nets for marine surface water sampling, bulk sampling with filtration, direct in situ filtration, and ex situ filtration (e.g. stainless steel bucket with filtration). Grab sampling, which is one of two primary methods (grab and continuous sampling) commonly used to sample water from bodies such as rivers, lakes or temporary events such as stormwater, was also employed. This technique is not, however, without limitations, especially for the sampling of marine surface water for microplastics analysis. For instance, water current flow may influence the microplastic abundance level, and there may be variation with sampled area and depth, which may not give a reliable result. Hence, to improve reproducibility, large sample volume is required for surface water. In this regard, sampling strategies will require additional equipment including vessels and flow meters, however, these have not been exploited very well to date in the studies under review.

The particle size range of microplastics to be detected and identified in sampled water is dependent on mesh size employed during sampling. Hence, mesh size is a very important point to consider before and during sampling process. The mesh sizes used for sampling in the various studies reviewed varied between 20 and 5000 μm. In the literature, 3–4.5 m long nets with a mesh size of about 300 μm is commonly used, and these can sample microplastics size of >300 μm (Browne, 2015). Only one study under review had used a mesh size of <300 μm (Briggs et al., 2019). Although the use of a lower mesh size is reported to improve microplastics detection limits, smaller or lower mesh net size will increase the likelihood or the possibility of clogging as a result of the presence of suspended organic matter. This could possibly explain why most of the reviewed studies used mesh sizes above 300 μm, thus preventing net clogging. Nonetheless, underestimation of microplastics in various environmental samples are inevitable due to lack of effective sampling devices capable of capturing the smaller microplastics or nanoplastics.

Sediment samples from coastal regions of beaches and rivers in Africa have been collected using direct sediment grabs (i.e. stainless spoons, stainless spatula etc.), sieving and collection in quadrats using corers. Since there could be uneven deposition of sediment, factors including the tideline, transects, intertidal, and depth of the sampling area should be critically considered. It should, however, be noted that boat and very special equipment (box corer, gravity corer) will be required to collect deeper and benthic sediment samples, which may not be readily available in most regions of the continent.

Contamination from sampling equipment during sampling campaigns have been reported to be a major concern in microplastics analysis (Prata et al., 2019). Most of the studies under review failed to report or consider sources of contamination during sampling. Few studies had control samples for their experiment (including sampling or field blanks), which makes the identification of any contamination source (s) difficult. Microplastics are present everywhere; therefore, quality control is crucial when carrying out sampling, because there are numerous potential sources of contamination, which should be avoided. For instance, sampling devices made of synthetic polymers must be substituted with non-plastic tools. Also, the introduction of control samples and quality control measures are recommended to prevent experimental error due to sampling instruments or sample handling. Quantity control is key to the overall accurate assessment of the microplastics abundance in field studies.

7. Analytical methods

Identification and quantification of microplastics in various environmental samples involves a combination of reliable analytical methods, as a single method cannot be adequate to elucidate microplastics from complex samples. These methods include visual sorting (for large microplastics, 1–5 mm size range), organic matter digestion, isolation using various techniques such as filtration, density separation, and staining. Thereafter, identification by microscopic or spectroscopic techniques such as FTIR or Raman can be carried out.

Microplastics particles present in dissected tissues of aquatic organisms are isolated using saline washes/density separation and organic material digestion before possible visual inspection and chemical identification (Lusher et al., 2017). To isolate microplastics, 43% of the studies under review successfully digested the excised tissues using potassium hydroxide (KOH) (e.g. KOH, 10%, 15%) with one study combining 10 M KOH and hydrogen peroxide (H_20_2) (34.5–36.5% *v*/v) (Akindele et al., 2020). These have been adapted for the dissolution of tissues of fish, mussel, and gastropod.

Surface water and sediment samples collected from the field may contain plastic particles of different polymer types, sizes, shapes, and color that must be separated or isolated (Hanvey et al., 2017). Microplastics on plankton nets and sieves used for surface water sampling are washed thoroughly several times with distilled water, or the bulk water samples are transferred into glass containers, density separated and/or filtered using either stainless steel sieves or glass fiber filters for identification.

For sediment samples, the most commonly used technique to extract microplastics in the studies reviewed was density separation using saturated salt solutions combined with filtration. This method was applied in 67% of the studies reviewed and involves introduction of a density separation salt solution (with a known density), stirring vigorously for a specific period, allowing the less dense particles to float to the surface and filtering out the particles into various size categories (Hanvey et al., 2017). In most of the studies reviewed, saturated sodium chloride (NaCl) (e.g. density: 1.2 g/cm^3, 140 g/L, 120 g/L, 100 g/L, 300 g/L) solution is applied (Abidli et al., 2018; de Villiers, 2018; de Villiers, 2019; Shabaka et al., 2019). NaCl is highly available, cheap, eco-friendly, and not toxic to the environment or humans (Hanvey et al., 2017; Nuelle et al., 2014; Sun et al., 2019). However, NaCl solution has been reported to be inefficient in extracting high-density microplastics (low recovery) such as polyethylene terephthalate (PET) (density; 1.31–1.43 g/cm^3), polyvinylchloride (PVC) (1.41–1.61 g/cm^3) or polyoxymethylene (1.20–1.58 g/cm^3) resulting in a possible underestimation of the reported data (Okoffo et al., 2019). Alternatively, high-density salt solutions such as calcium chloride ($CaCl_2$) (1.5 g/cm^3), zinc chloride ($ZnCl_2$) (1.5–1.7 g/cm^3) or sodium iodide (NaI) (1.6–1.8 g/cm^3) has been recommended to improve extraction efficiencies and estimations, (Hurley et al., 2018; Quinn et al., 2017) however, their usage are limited in studies in Africa. Only a few studies under review had used NaI (1.6 g/cm^3) and $ZnCl_2$ solution (1.7–1.8 g/cm^3) (Matsuguma et al., 2017; Missawi et al., 2020). It should, however, be noted that denser salts solutions have been reported to be expensive and can pollute the environment if not handled properly, which might have limited their usage in these studies. Nevertheless, a combination of salt solutions to get high recovery rates of particles, especially for heavier polymers, is recommended for microplastics studies in Africa. Studies are also recommended to explore the extraction efficiencies of salts solutions used on known microplastics fortified samples before being used on environmental samples.

Few of the studies under review applied digestion or purification procedures aimed at eliminating organic matter from surface water and sediment samples with the common agents being hydrogen peroxide (H_2O_2) (e.g. 30% H_2O_2) (Gbogbo et al., 2020; Matsuguma et al., 2017) and Fenton reagent (H_2O_2 + Fe) (Briggs et al., 2019; Migwi et al., 2020). The presence of organic matter in samples has been reported to hinder proper identification of microplastics, hence proper attention is needed. It is recommended that microplastics researchers in Africa should combine density separation with organic material removal or degradation steps to increase the extraction efficiencies and identification of microplastics particles.

Visual identification of microplastics observed either directly or under a stereoscope or microscope, was the most common method reported (52%, Fig. 5). However, this method has been reported to be subjective (as it is prone to human or observer error), time consuming, size-dependent and may lead to under or overestimation of microplastics (Coppock et al., 2017; Nel et al., 2019; Okoffo et al., 2019; Prata et al., 2019). To assess how color (white, green and blue) and size (large; ~1000 μm and small; <400 μm) of plastic microbead influences underestimation as a result of observer error and/or technical error for example, Nel et al., 2019 inoculated sediment samples varying in grain size with known quantities of low-density polyethylene microbeads and observed an overall underestimation of 78.59% (Nel et al., 2019). The technique has also been critiqued for proving difficulty in distinctive analysis between synthetic and natural fibers. For example, Hidalgo-Ruz et al., 2012 reported that microplastics characterized visually as plastics were not confirmed following chemical analysis with a presumed 70% error of plastics (Hidalgo-Ruz et al., 2012). To improve visual inspection technique and minimize observer error, some studies in this review have tried testing microplastics with a hot needle (Dahms et al., 2020) and using staining dyes on particles (Chouchene et al., 2019; Gbogbo et al., 2020) to increase accuracy to some extent.

Chemical characterization of isolated microplastics by Fourier transform infrared spectroscopy (FTIR) and Raman spectroscopy to confirm their identity has been recommended to increase the accuracy of visual counting/inspection or identification using microscopy (Hanvey et al., 2017) This was the case in most of the studies reviewed as a combination of microscopy and spectroscopy (i.e., microscope and FTIR) were used. From the various studies reviewed, 38% (Fig. 5) had access to or used FTIR in analyzing microplastic particles extracted with less than 5% presenting spectra of these polymers in their studies. The remaining used Raman (Missawi et al., 2020), Scanning Electron Microscopy (SEM) (Briggs et al., 2019; Chouchene et al., 2019) and Differential Scanning Calorimetry (DSC) (Shabaka et al., 2019) techniques for polymer identification. FTIR is capable of characterizing microplastic particles >20 um in size while Raman microscopy allows the characterization of microplastics <20 μm (but >1 um) (Okoffo et al., 2020). These techniques are however not suitable for nano-sized particles (<0.1 μm) identification, a major analytical challenge in microplastics research across the world today. Some of the reviewed studies identified the non-availability of FTIR or Raman as the limitation encountered during their research. That notwithstanding, the results could be at best presented as potential microplastics rather than reaching a definitive conclusion on the abundance of microplastics in such environmental samples. FTIR and micro-Raman spectroscopy are not readily available everywhere (Majewsky et al., 2016) and could be a problem for most research laboratory in developing countries.

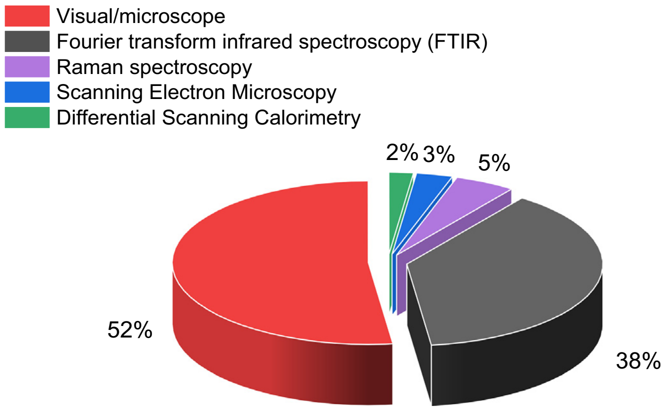


Fig. 5. Distribution of analytical methods used to identify microplastics across all studies under review.

Although there is currently no universally accepted analytical methods available for microplastics analysis, emerging novel alternatives include Pyrolysis-gas chromatography coupled with mass spectrometry (Pyr-GC/MS), thermal desorption gas chromatography mass spectrometry (TED-GC/MS), thermogravimetric analysis coupled with differential scanning calorimetry (TGA-DSC), Pressurized liquid extraction (PLE) combined with Pyr-GC/MS and Liquid chromatography (Okoffo et al., 2019; Okoffo et al., 2020). The application of these techniques, however, remains unexplored in studies in Africa.

8. Conclusion and research gaps

This study provides an overview of microplastic occurrence and distribution in different environmental matrices and organisms in Africa as well as the associated contaminants. Generally, in the last five years, appreciable increase has been observed with respect to understanding the occurrence and distribution of microplastics in different environmental compartment across the continent. However, as this area of research is fast emerging globally, there exist limited information in terms of empirical data on microplastic pollution status in Africa. For instance, a total of 15 studies were carried out on freshwater/marine surface waters, 22 studies for sediment samples and 22 studies for microplastic in aquatic organisms. Studies in the marine environment are higher than freshwater systems (Figs. 2 and S1). Considering the number of countries in the continent, only 20.4% (11 of 54) have done at least one study on microplastics abundance and 11% (6 of 54) on microplastics interaction with contaminants. The highest occurring plastic type in all studies are polyethylene > polypropylene > polystyrene > polyethylene terephthalate > nylon which slightly correlates with global plastic demand and may reflect the plastic demand in the continent. Most studies come from South Africa > Nigeria > Tunisia > other 10 countries. Even with these studies, there still exist a huge gap in our understanding of microplastic fate in Africa, namely,

- Freshwater systems serve as a major channel for microplastics pollution from land-based sources which will eventually discharge their contents into the marine environment. Two major Rivers in Africa (Nile and Niger) have been reported to be among the top ten polluters of the sea globally. This was predicted using the mismanaged plastic waste generated in the River catchments to be between 6919 and 84,792 and 3185–35,196 tons/year for River Nile and River Niger, respectively (Schmidt et al., 2017). Although one study has been conducted on River Nile regarding microplastics in two fish species (Khan et al., 2020), no study has investigated the presence, concentration, and composition of microplastics in surface waters or sediment in these two Rivers. Therefore, more studies are needed in these major systems.

- There are currently no microplastic studies on the terrestrial environment. The contribution of land-based sources to freshwater/marine systems across the continent is unknown. By understanding these links, proper control measures can be implemented.
- There is a need to identify model organisms that can be used in ecotoxicological assessment on the continent in other to predict the effect/impact of microplastic on living organisms.
- Some of the studies reviewed did not include appropriate procedural or experimental control which is not a good practice. In other to avoid under or over estimation of microplastic concentrations, appropriate controls must be introduced and reported.
- Most of the studies relied on visual identification (52%) to identify microplastic. Efficient sampling and detection methods are vital to understanding the distributions of microplastics across the countries in Africa. Lack of modern scientific equipment including Raman, FTIR, and Pyrolysis GC–MS were identified as a major setback for microplastic research in the various studies reviewed. Although we are cautious in our assessment, as most of the equipment is quite expensive and are not readily available, we recommend funding of African research in this regard and collaboration with other international laboratories.
- There is limited information on the interaction of metals and microplastics in Africa. Only one study in Nigeria examined the levels of 27 trace metals in beach pellets. More studies are needed in this area to fully understand the risks associated with microplastics in Africa.
- Also, to date, no study has examined the microplastics abundance in atmospheric air in Africa. Research in this area is urgently required as some African countries have been reported as being among the leading countries in air pollution worldwide (Bauer et al., 2019). This is crucial to the overall risk assessment of microplastics on the continent of Africa.

We therefore recommend that various organizations both private and government/public units should invest in microplastic research. Also, educational institutions across Africa must cultivate young researchers in this field of study as there are limited experts presently on the continent. Effective policy formulation depends on the availability of reliable data on the occurrence, distribution, transport and environmental consequences of microplastics. Government at all levels should encourage research to enhance acquisition of knowledge on plastic pollution in the environment. This will, in turn, assist the government in policy formulation and regulation of plastic pollution in the environment. There is a need for more attention in terms of policies which could help to improve better plastic waste management across the continent, which can only be achieved through research.

CRediT authorship contribution statement

Olubukola S. Alimi: Methodology, Investigation, Visualization, Writing- Original draft, and Resources.

Oluniyi O. Fadare: Conceptualization, Methodology, Investigation, Visualization, Writing- Original draft, and Resources.

Elvis D. Okoffo: Investigation, Visualization, Writing-Reviewing and Editing, and Resources.

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.

Acknowledgements

The authors acknowledge the support of the National Universities Commission (NUC) and Petroleum Technology Development Fund (PTDF), Nigeria for an award to OSA, McGill University for a MEDA and Eugenie Ulmer-Lamothe award and NSERC PURE CREATE for a scholarship to OSA. The authors also acknowledge the support given to EDO under the Research Training Scholarship awarded by the University of Queensland and the Queensland Alliance for Environmental Health Sciences (QAEHS) and also a QAEHS Research Higher Degree Top-Up Scholarship.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.142422.

References

Abidli, S., Toumi, H., Lahbib, Y., El Menif, N.T., 2017. The first evaluation of microplastics in sediments from the complex lagoon-channel of Bizerte (Northern Tunisia). Water, Air, Soil Pollut. 228 (7), 262.

Abidli, S., Antunes, J.C., Ferreira, J.L., Lahbib, Y., Sobral, P., El Menif, N.T., 2018. Microplastics in sediments from the littoral zone of the north Tunisian coast (Mediterranean Sea). Estuar. Coast. Shelf Sci. 205, 1–9.

Abidli, S., Lahbib, Y., El Menif, N.T., 2019. Microplastics in commercial molluscs from the lagoon of Bizerte (Northern Tunisia). Mar. Pollut. Bull. 142, 243–252.

Adeogun, A.O., Ibor, O.R., Khan, E.A., Chukwuka, A.V., Omogbemi, E.D., Arukwe, A., 2020. Detection and occurrence of microplastics in the stomach of commercial fish species from a municipal water supply lake in southwestern Nigeria. Environ. Sci. Pollut. Res. 1-11.

Adika, S.A., Mahu, E., Crane, R., Marchant, R., Montford, J., Folorunsho, R., Gordon, C., 2020. Microplastic ingestion by pelagic and demersal fish species from the Eastern Central Atlantic Ocean, off the Coast of Ghana. Mar. Pollut. Bull. 153, 110998.

Akindele, E.O., Ehlers, S.M., Koop, J.H.E., 2019. First empirical study of freshwater microplastics in West Africa using gastropods from Nigeria as bioindicators. Limnologica 78, 125708.

Akindele, E.O., Ehlers, S.M., Koop, J.H., 2020. Freshwater insects of different feeding guilds ingest microplastics in two Gulf of Guinea tributaries in Nigeria. Environ. Sci. Pollut. Res. 27 (26), 33373–33379.

Alimi, O.S., Farner Budarz, J., Hernandez, L.M., Tufenkji, N., 2018. Microplastics and nanoplastics in aquatic environments: aggregation, deposition, and enhanced contaminant transport. Environ. Sci. Technol. 52 (4), 1704–1724.

Babayemi, J.O., Nnorom, I.C., Osibanjo, O., Weber, R., 2019. Ensuring sustainability in plastics use in Africa: consumption, waste generation, and projections. Environ. Sci. Eur. 31 (1), 60.

Ballent, A., Corcoran, P.L., Madden, O., Helm, P.A., Longstaffe, F.J., 2016. Sources and sinks of microplastics in Canadian Lake Ontario nearshore, tributary and beach sediments. Mar. Pollut. Bull. 110 (1), 383–395.

Bauer, S.E., Im, U., Mezuman, K., Gao, C.Y., 2019. Desert dust, industrialization, and agricultural fires: health impacts of outdoor air pollution in Africa. J. Geophys. Res. Atmos. 124 (7), 4104–4120.

Benson, N.U., Fred-Ahmadu, O.H., 2020. Occurrence and distribution of microplastics-sorbed phthalic acid esters (PAEs) in coastal psammitic sediments of tropical Atlantic Ocean, Gulf of Guinea. Sci. Total Environ. 139013.

Biginagwa, F.J., Mayoma, B.S., Shashoua, Y., Syberg, K., Khan, F.R., 2016. First evidence of microplastics in the African Great Lakes: recovery from Lake Victoria Nile perch and Nile tilapia. J. Great Lakes Res. 42 (1), 146–149.

Bouchentouf, S., Driss, A.T., 2013. Abundance of plastic debris in intertidal surface sediments from Arzew Gulf (Western Algeria). Am. J. Sci. 1 (1), 28–32.

Briggs, E., de Moura, E.A.B., Furusawa, H.A., Cotrim, M.E.B., Oguzie, E.E., Lugao, A.B., 2019. Microplastics: A Novel Method for Surface Water Sampling and Sample Extraction in Elechi Creek, Rivers State, Nigeria. Springer International Publishing, Cham, pp. 269–281.

Browne, M.A., 2015. Marine Anthropogenic Litter. Springer, Cham, pp. 229–244.

Bruce-Vanderpuije, P., Megson, D., Reiner, E.J., Bradley, L., Adu-Kumi, S., Gardella, J.A., 2019. The state of POPs in Ghana- a review on persistent organic pollutants: environmental and human exposure. Environ. Pollut. 245, 331–342.

Chouchene, K., da Costa, J.P., Wali, A., Girão, A.V., Hentati, O., Duarte, A.C., Rocha-Santos, T., Ksibi, M., 2019. Microplastic pollution in the sediments of Sidi Mansour Harbor in Southeast Tunisia. Mar. Pollut. Bull. 146, 92–99.

Coppock, R.L., Cole, M., Lindeque, P.K., Queirós, A.M., Galloway, T.S., 2017. A small-scale, portable method for extracting microplastics from marine sediments. Environ. Pollut. 230, 829–837.

Dahms, H.T.J., van Rensburg, G.J., Greenfield, R., 2020. The microplastic profile of an urban African stream. Sci. Total Environ. 731, 138893.

de Sá, L.C., Oliveira, M., Ribeiro, F., Rocha, T.L., Futter, M.N., 2018. Studies of the effects of microplastics on aquatic organisms: what do we know and where should we focus our efforts in the future? Sci. Total Environ. 645, 1029–1039.

de Villiers, S., 2018. Quantification of microfibre levels in South Africa's beach sediments, and evaluation of spatial and temporal variability from 2016 to 2017. Mar. Pollut. Bull. 135, 481–489.

de Villiers, S., 2019. Microfibre pollution hotspots in river sediments adjacent to South Africa's coastline. Water SA 45 (1), 97–102.

Do Sul, J.A.I., Costa, M.F. and Fillmann, G. 2014. Microplastics in the pelagic environment around oceanic islands of the Western Tropical Atlantic Ocean. Water, Air, Soil Pollut. 225(7), 2004.

Eerkes-Medrano, D., Thompson, R.C., Aldridge, D.C., 2015. Microplastics in freshwater systems: a review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. Water Res. 75, 63–82.

Endo, S., Takizawa, R., Okuda, K., Takada, H., Chiba, K., Kanehiro, H., Ogi, H., Yamashita, R., Date, T., 2005. Concentration of polychlorinated biphenyls (PCBs) in beached resin pellets: variability among individual particles and regional differences. Mar. Pollut. Bull. 50 (10), 1103–1114.

Enyoh, C.E., Wirnkor, V.A., Ngozi, V.E., Chukwuemeka, I.S., 2019. Macrodebris and Microplastics Pollution in Nigeria: First Report on Abundance, Distribution and Composition (Preprints).

Fadare, O.O., Wan, B., Guo, L.-H., Xin, Y., Qin, W., Yang, Y., 2019. Humic acid alleviates the toxicity of polystyrene nanoplastic particles to Daphnia magna. Environ. Sci. Nano 6 (5), 1466–1477.

Fred-Ahmadu, O.H., Ayejuyo, O.O., Benson, N.U., 2020. Dataset on microplastics and associated trace metals and phthalate esters in sandy beaches of coastal Atlantic ecosystem of Lagos, Nigeria. Data Brief 105755.

Free, C.M., Jensen, O.P., Mason, S.A., Eriksen, M., Williamson, N.J., Boldgiv, B., 2014. High-levels of microplastic pollution in a large, remote, mountain lake. Mar. Pollut. Bull. 85 (1), 156–163.

Galloway, T.S., Cole, M., Lewis, C., 2017. Interactions of microplastic debris throughout the marine ecosystem. Nature Ecology & Evolution 1 (5), 1–8.

Gbogbo, F., Takyi, J.B., Billah, M.K., Ewool, J., 2020. Analysis of microplastics in wetland samples from coastal Ghana using the Rose Bengal stain. Environ. Monit. Assess. 192 (4), 1–10.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3 (7), e1700782.

Hamid, F.S., Bhatti, M.S., Anuar, N., Anuar, N., Mohan, P., Periathamby, A., 2018. Worldwide distribution and abundance of microplastic: how dire is the situation? Waste Manage. Res. 36 (10), 873–897.

Hanvey, J.S., Lewis, P.J., Lavers, J.L., Crosbie, N.D., Pozo, K., Clarke, B.O., 2017. A review of analytical techniques for quantifying microplastics in sediments. Anal. Methods 9 (9), 1369–1383.

Hermabessiere, L., Dehaut, A., Paul-Pont, I., Lacroix, C., Jezequel, R., Soudant, P., Duflos, G., 2017. Occurrence and effects of plastic additives on marine environments and organisms: a review. Chemosphere 182, 781–793.

Herrera, A., Ŝtindlová, A., Martínez, I., Rapp, J., Romero-Kutzner, V., Samper, M.D., Montoto, T., Aguiar-González, B., Packard, T., Gómez, M., 2019. Microplastic ingestion by Atlantic chub mackerel (Scomber colias) in the Canary Islands coast. Mar. Pollut. Bull. 139, 127–135.

Hidalgo-Ruz, V., Gutow, L., Thompson, R.C., Thiel, M., 2012. Microplastics in the marine environment: a review of the methods used for identification and quantification. Environ. Sci. Technol. 46 (6), 3060–3075.

Hong, S.H., Shim, W.J., Jang, M., 2018. Microplastic Contamination in Aquatic Environments. Elsevier, pp. 271–315.

Hosoda, J., Ofosu-Anim, J., Sabi, E.B., Akita, L.G., Onwona-Agyeman, S., Yamashita, R., Takada, H., 2014. Monitoring of organic micropollutants in Ghana by combination of pellet watch with sediment analysis: e-waste as a source of PCBs. Mar. Pollut. Bull. 86 (1–2), 575–581.

Hurley, R.R., Lusher, A.L., Olsen, M., Nizzetto, L., 2018. Validation of a method for extracting microplastics from complex, organic-rich, environmental matrices. Environ. Sci. Technol. 52 (13), 7409–7417.

Iheanacho, S.C., Odo, G.E., 2020a. Dietary exposure to polyvinyl chloride microparticles induced oxidative stress and hepatic damage in Clarias gariepinus (Burchell, 1822). Environ. Sci. Pollut. Res. 1–15.

Iheanacho, S.C., Odo, G.E., 2020b. Neurotoxicity, oxidative stress biomarkers and haematological responses in African catfish (Clarias gariepinus) exposed to polyvinyl chloride microparticles. Comp. Biochem. Phys. C. 232, 108741.

Ilechukwu, I., Ndukwe, G.I., Mgbemena, N.M., Akandu, A.U., 2019. Occurrence of microplastics in surface sediments of beaches in Lagos, Nigeria. European Chemical Bulletin 8 (11), 371–375.

Iwalaye, O.A., Moodley, G.K., Robertson-Andersson, D.V., 2020. The possible routes of microplastics uptake in sea cucumber Holothuria cinerascens (Brandt, 1835). Environ. Pollut. 264, 114644.

Jambeck, J., Hardesty, B.D., Brooks, A.L., Friend, T., Teleki, K., Fabres, J., Beaudoin, Y., Bamba, A., Francis, J., Ribbink, A.J., Baleta, T., Bouwman, H., Knox, J., Wilcox, C., 2018. Challenges and emerging solutions to the land-based plastic waste issue in Africa. Mar. Policy 96, 256–263.

Khan, F.R., Shashoua, Y., Crawford, A., Drury, A., Sheppard, K., Stewart, K., Sculthorp, T., 2020. 'The plastic Nile': first evidence of microplastic contamination in fish from the Nile River (Cairo, Egypt). Toxics 8 (2), 22.

Koelmans, A.A., Mohamed Nor, N.H., Hermsen, E., Kooi, M., Mintenig, S.M., De France, J., 2019. Microplastics in freshwaters and drinking water: critical review and assessment of data quality. Water Res. 155, 410–422.

Kosore, C., Ojwang, L., Maghanga, J., Kamau, J., Kimeli, A., Omukoto, J., Ngisiag'e, N., Mwaluma, J., Ong'ada, H., Magori, C., 2018. Occurrence and ingestion of microplastics by zooplankton in Kenya's marine environment: first documented evidence. Afr. J. Mar. Sci. 40 (3), 225–234.

La Daana, K.K., Officer, R., Lyashevska, O., Thompson, R.C., O'Connor, I., 2017. Microplastic abundance, distribution and composition along a latitudinal gradient in the Atlantic Ocean. Mar. Pollut. Bull. 115 (1–2), 307–314.

Liebezeit, G., Dubaish, F., 2012. Microplastics in beaches of the East Frisian islands Spiekeroog and Kachelotplate. B. Environ. Contam. Tox. 89 (1), 213–217.

Lourenço, P.M., Serra-Gonçalves, C., Ferreira, J.L., Catry, T., Granadeiro, J.P., 2017. Plastic and other microfibers in sediments, macroinvertebrates and shorebirds from three intertidal wetlands of southern Europe and west Africa. Environ. Pollut. 231, 123–133.

Lusher, A.L., Welden, N.A., Sobral, P., Cole, M., 2017. Sampling, isolating and identifying microplastics ingested by fish and invertebrates. Anal. Methods 9 (9), 1346–1360.

Majewsky, M., Bitter, H., Eiche, E., Horn, H., 2016. Determination of microplastic polyethylene (PE) and polypropylene (PP) in environmental samples using thermal analysis (TGA-DSC). Sci. Total Environ. 568, 507–511.

Matsuguma, Y., Takada, H., Kumata, H., Kanke, H., Sakurai, S., Suzuki, T., Itoh, M., Okazaki, Y., Boonyatumanond, R., Zakaria, M.P., 2017. Microplastics in sediment cores from Asia and Africa as indicators of temporal trends in plastic pollution. Arch. Environ. Contam. Toxicol. 73 (2), 230–239.

Mbedzi, R., Cuthbert, R.N., Wasserman, R.J., Murungweni, F.M., Dalu, T., 2020a. Spatiotemporal variation in microplastic contamination along a subtropical reservoir shoreline. Environ. Sci. Pollut. Res. 1-8.

Mbedzi, R., Dalu, T., Wasserman, R.J., Murungweni, F., Cuthbert, R.N., 2020b. Functional response quantifies microplastic uptake by a widespread African fish species. Sci. Total Environ. 700, 134522.

Merga, L.B., Redondo-Hasselerharm, P.E., Van den Brink, P.J., Koelmans, A.A., 2020. Distribution of microplastic and small macroplastic particles across four fish species and sediment in an African lake. Sci. Total Environ. 741, 140527.

Migwi, F.K., Ogunah, J.A., Kiratu, J.M., 2020. Occurrence and spatial distribution of microplastics in the surface waters of Lake Naivasha, Kenya. Environ. Toxicol. Chem. 39 (4), 765–774.

Missawi, O., Bousserrhine, N., Belbekhouche, S., Zitouni, N., Alphonse, V., Boughattas, I., Banni, M., 2020. Abundance and distribution of small microplastics (≤ 3 μm) in sediments and seaworms from the Southern Mediterranean coasts and characterisation of their potential harmful effects. Environ. Pollut. 114634.

Naidoo, T., Glassom, D., 2019. Sea-surface microplastic concentrations along the coastal shelf of KwaZulu–Natal, South Africa. Mar. Pollut. Bull. 149, 110514.

Naidoo, T., Glassom, D., Smit, A.J., 2015. Plastic pollution in five urban estuaries of KwaZulu-Natal, South Africa. Mar. Pollut. Bull. 101 (1), 473–480.

Naidoo, T., Smit, A.J., Glassom, D., 2016. Plastic ingestion by estuarine mullet Mugil cephalus (Mugilidae) in an urban harbour, KwaZulu-Natal, South Africa. Afr. J. Mar. Sci. 38 (1), 145–149.

Naidoo, T., Thompson, R.C., Rajkaran, A., 2020. Quantification and characterisation of microplastics ingested by selected juvenile fish species associated with mangroves in KwaZulu-Natal, South Africa. Environ. Pollut. 257, 113635.

Naik, R.K., Naik, M.M., D'Costa, P.M., Shaikh, F., 2019. Microplastics in ballast water as an emerging source and vector for harmful chemicals, antibiotics, metals, bacterial pathogens and HAB species: a potential risk to the marine environment and human health. Mar. Pollut. Bull. 149, 110525.

Nel, H.A., Froneman, P.W., 2015. A quantitative analysis of microplastic pollution along the south-eastern coastline of South Africa. Mar. Pollut. Bull. 101 (1), 274–279.

Nel, H.A., Froneman, P.W., 2018. Presence of microplastics in the tube structure of the reef-building polychaete Gunnarea gaimardi (Quatrefages 1848). Afr. J. Mar. Sci. 40 (1), 87–89.

Nel, H.A., Hean, J.W., Noundou, X.S., Froneman, P.W., 2017. Do microplastic loads reflect the population demographics along the southern African coastline? Mar. Pollut. Bull. 115 (1–2), 115–119.

Nel, H.A., Dalu, T., Wasserman, R.J., 2018. Sinks and sources: assessing microplastic abundance in river sediment and deposit feeders in an Austral temperate urban river system. Sci. Total Environ. 612, 950–956.

Nel, H.A., Dalu, T., Wasserman, R.J., Hean, J.W., 2019. Colour and size influences plastic microbead underestimation, regardless of sediment grain size. Sci. Total Environ. 655, 567–570.

Nuelle, M.-T., Dekiff, J.H., Remy, D., Fries, E., 2014. A new analytical approach for monitoring microplastics in marine sediments. Environ. Pollut. 184, 161–169.

Okoffo, E.D., O'Brien, S., O'Brien, J.W., Tscharke, B.J., Thomas, K.V., 2019. Wastewater treatment plants as a source of plastics in the environment: a review of occurrence, methods for identification, quantification and fate. Environmental Science: Water Research & Technology 5 (11), 1908–1931.

Okoffo, E.D., Ribeiro, F., O'Brien, J.W., O'Brien, S., Tscharke, B.J., Gallen, M., Samanipour, S., Mueller, J.F., Thomas, K.V., 2020. Identification and quantification of selected plastics in biosolids by pressurized liquid extraction combined with double-shot pyrolysis gas chromatography–mass spectrometry. Sci. Total Environ. 715, 136924.

Oni, B.A., Ayeni, A.O., Agboola, O., Oguntade, T., Obanla, O., 2020. Comparing microplastics contaminants in (dry and raining) seasons for Ox-Bow Lake in Yenagoa. Nigeria. Ecotoxicol. Environ. Saf. 198, 110656.

Plastics Europe, 2019. Plastics-The Facts. An analysis of European plastics production, demand and waste data. Retrieved from https://www.plasticseurope.org/application/files/9715/7129/9584/FINAL_web_version_Plastics_the_facts2019_14102019.pdf.

Prata, J.C., da Costa, J.P., Duarte, A.C., Rocha-Santos, T., 2019. Methods for sampling and detection of microplastics in water and sediment: a critical review. TrAC, Trends Anal Chem. 110, 150–159.

Qiu, Q., Peng, J., Yu, X., Chen, F., Wang, J., Dong, F., 2015. Occurrence of microplastics in the coastal marine environment: first observation on sediment of China. Mar. Pollut. Bull. 98 (1–2), 274–280.

Quinn, B., Murphy, F., Ewins, C., 2017. Validation of density separation for the rapid recovery of microplastics from sediment. Anal. Methods 9 (9), 1491–1498.

Reynolds, C., Ryan, P.G., 2018. Micro-plastic ingestion by waterbirds from contaminated wetlands in South Africa. Mar. Pollut. Bull. 126, 330–333.

Rezania, S., Park, J., Din, M.F.M., Taib, S.M., Talaiekhozani, A., Yadav, K.K., Kamyab, H., 2018. Microplastics pollution in different aquatic environments and biota: a review of recent studies. Mar. Pollut. Bull. 133, 191–208.

Ribeiro, F., O'Brien, J.W., Galloway, T., Thomas, K.V., 2019. Accumulation and fate of nano- and micro-plastics and associated contaminants in organisms. TrAC, Trends Anal Chem. 111, 139–147.

Ribeiro, F., Okoffo, E.D., O'Brien, J.W., Fraissinet-Tachet, S., O'Brien, S., Gallen, M., Samanipour, S., Kaserzon, S., Mueller, J.F., Galloway, T., Thomas, K.V., 2020. Quantitative analysis of selected plastics in high commercial value Australian seafood by pyrolysis gas chromatography mass spectrometry. Environ. Sci. Technol. 54 (15), 9408–9417. https://doi.org/10.1021/acs.est.0c02337.

Rochman, C.M., 2015. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer International Publishing, Cham, pp. 117–140.

Rochman, C.M., Tahir, A., Williams, S.L., Baxa, D.V., Lam, R., Miller, J.T., Teh, F.-C., Werorilangi, S., Teh, S.J., 2015. Anthropogenic debris in seafood: plastic debris and fibers from textiles in fish and bivalves sold for human consumption. Sci. Rep. 5 (1), 14340.

Ryan, P.G., 1987. The incidence and characteristics of plastic particles ingested by seabirds. Mar. Environ. Res. 23 (3), 175–206.

Ryan, P.G., 1988. The characteristics and distribution of plastic particles at the sea-surface off the southwestern Cape Province. South Africa. Mar. Environ. Res. 25 (4), 249–273.

Ryan, P., Moloney, C., 1990. Plastic and other artefacts on South African beaches: temporal trends in abundance and composition. S. AFR. J. SCI./S.-AFR. TYDSKR. WET. 86 (7), 450–452.

Ryan, P.G., Bouwman, H., Moloney, C.L., Yuyama, M., Takada, H., 2012. Long-term decreases in persistent organic pollutants in South African coastal waters detected from beached polyethylene pellets. Mar. Pollut. Bull. 64 (12), 2756–2760.

Sayre, A.P., 1999. Africa. Twenty-First Century Books.

Schmidt, C., Krauth, T., Wagner, S., 2017. Export of plastic debris by Rivers into the sea. Environ. Sci. Technol. 51 (21), 12246–12253.

Shabaka, S.H., Ghobashy, M., Marey, R.S., 2019. Identification of marine microplastics in Eastern Harbor, Mediterranean Coast of Egypt, using differential scanning calorimetry. Mar. Pollut. Bull. 142, 494–503.

Shabaka, S.H., Marey, R.S., Ghobashy, M., Abushady, A.M., Ismail, G.A., Khairy, H.M., 2020. Thermal analysis and enhanced visual technique for assessment of microplastics in fish from an Urban Harbor, Mediterranean Coast of Egypt. Mar. Pollut. Bull. 159, 111465.

Shim, W.J., Hong, S.H., Eo, S.E., 2017. Identification methods in microplastic analysis: a review. Anal. Methods 9 (9), 1384–1391.

Shim, W.J., Hong, S.H., Eo, S., 2018. In: Zeng, E.Y. (Ed.), Microplastic Contamination in Aquatic Environments. Elsevier, pp. 1–26.

Sparks, C., 2020. Microplastics in mussels along the coast of Cape Town. South Africa. Bull. Environ. Contam. Toxicol. 104 (4), 423–431.

Sparks, C., Immelman, S., 2020. Microplastics in offshore fish from the Agulhas Bank, South Africa. Mar. Pollut. Bull. 156, 111216.

Sun, J., Dai, X., Wang, Q., van Loosdrecht, M.C.M., Ni, B.-J., 2019. Microplastics in wastewater treatment plants: detection, occurrence and removal. Water Res. 152, 21–37.

Takada, H., 2006. Call for pellets! International pellet watch global monitoring of POPs using beached plastic resin pellets. Mar. Pollut. Bull. 52 (12), 1547–1548.

Taniguchi, S., Colabuono, F.I., Dias, P.S., Oliveira, R., Fisner, M., Turra, A., Izar, G.M., Abessa, D.M.S., Saha, M., Hosoda, J., 2016. Spatial variability in persistent organic pollutants and polycyclic aromatic hydrocarbons found in beach-stranded pellets along the coast of the state of São Paulo, southeastern Brazil. Mar. Pollut. Bull. 106 (1–2), 87–94.

Tata, T., Belabed, B.E., Bououdina, M., Bellucci, S., 2020. Occurrence and characterization of surface sediment microplastics and litter from North African coasts of Mediterranean Sea: preliminary research and first evidence. Sci. Total Environ. 713, 136664.

Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W., McGonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? Sci 304 (5672), 838.

Toumi, H., Abidli, S., Bejaoui, M., 2019. Microplastics in freshwater environment: the first evaluation in sediments from seven water streams surrounding the lagoon of Bizerte (Northern Tunisia). Environ. Sci. Pollut. Res. 26 (14), 14673–14682.

Tsang, Y.Y., Mak, C.W., Liebich, C., Lam, S.W., Sze, E.T., Chan, K.M., 2017. Microplastic pollution in the marine waters and sediments of Hong Kong. Mar. Pollut. Bull. 115 (1–2), 20–28.

United-Nations, 2019. World Population Prospects – Population Division. United Nations Department of Economic and Social Affairs, Population Division.

Vallee, D., Margat, J., Eliasson, A., Hoogeveen, J., 2003. Review of World Water Resources by Country (Food and Agricultural Organization of the United Nations).

Van Cauwenberghe, L., Devriese, L., Galgani, F., Robbens, J., Janssen, C.R., 2015. Microplastics in sediments: a review of techniques, occurrence and effects. Mar. Environ. Res. 111, 5–17.

Vedolin, M.C., Teophilo, C.Y.S., Turra, A., Figueira, R.C.L., 2018. Spatial variability in the concentrations of metals in beached microplastics. Mar. Pollut. Bull. 129 (2), 487–493.

Weideman, E.A., Perold, V., Ryan, P.G., 2019. Little evidence that dams in the Orange–Vaal River system trap floating microplastics or microfibres. Mar. Pollut. Bull. 149, 110664.

Woodall, L.C., Sanchez-Vidal, A., Canals, M., Paterson, G.L.J., Coppock, R., Sleight, V., Calafat, A., Rogers, A.D., Narayanaswamy, B.E., Thompson, R.C., 2014. The deep sea is a major sink for microplastic debris. R. Soc. Open Sci. 1 (4), 140317.

Yang, J., Cang, L., Sun, Q., Dong, G., Ata-Ul-Karim, S.T., Zhou, D., 2019. Effects of soil environmental factors and UV aging on Cu2+ adsorption on microplastics. Environ. Sci. Pollut. Res. 26 (22), 23027–23036.

Yeo, B.G., Takada, H., Hosoda, J., Kondo, A., Yamashita, R., Saha, M., Maes, T., 2017. Polycyclic aromatic hydrocarbons (PAHs) and hopanes in plastic resin pellets as markers of oil pollution via international pellet watch monitoring. Arch. Environ. Contam. Toxicol. 73 (2), 196–206.

Zitouni, N., Bousserrhine, N., Belbekhouche, S., Missawi, O., Alphonse, V., Boughatass, I., Banni, M., 2020. First report on the presence of small microplastics (≤ 3 μm) in tissue of the commercial fish Serranus scriba (Linnaeus. 1758) from Tunisian coasts and associated cellular alterations. Environ. Pollut. 114576.