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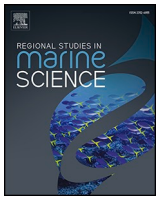
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Occurrence, spatial distribution, and source apportionment of microplastics in Durban Bay, South Africa

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ABSTRACT

Globally, microplastics have been identified in a diverse range of environments. However, the extent of microplastic pollution in South Africa's context is largely lacking. In this study, an investigation of microplastic pollution was conducted across the Durban Bay harbour located in the province of KwaZulu-Natal, South Africa. Microplastic evaluation was performed both on surface water and sediment samples, collected from various spots across the harbour. Microplastics were extracted and analysed for their characteristics using visual identification on stereomicroscopes, and chemical characterisation using Raman-microscopy. Microplastics were detected in all samples, with abundances of up to 80.72 MP m^{-3} in surface water samples, and 1.76 MP g^{-1} in sediments. Fibres and fragments were the most observed morphologies in both surface water and sediment samples. In this case, the detected fibres comprised up to 75.68% in surface waters, and 45.54% in sediments, while fragments reached 19.84% in surface waters, and 41.07% in sediment samples. Polyethylene, polypropylene, and polyester were the most dominant polymers observed in the investigated samples. In general, higher microplastic abundances were found in the study sites located near the river inflows and stormwater drains, with anthropogenic activities such as shipping bays. Overall, the microplastic abundance in Durban Bay was comparable with the levels found in other studies within South Africa and across the globe.

1. Introduction

The durability, wide application, and cheap production of plastics have promoted their incorporation into a variety of products. However, these design characteristics present threats to the health of ecosystems (Miller et al., 2021). The increased production and exponential usage of plastics, since the beginning of their industrial production in the 1950 s, has led to an abundance of synthetic polymers being found across terrestrial, freshwater, and marine ecosystems (Wang and Wang, 2018). The large volume of plastic waste accumulating in the environment has developed into one of the most pervasive problems of the anthropogenic era, with as much as 80% of litter in the oceans being plastic (Hartmann et al., 2019). Plastics have been detected in remote regions, originating from various sources, such as landfills, shipping activities, and fisheries; and are transported via ocean currents, wind, sea ice, or biota (Lusher et al., 2015). The ocean has long been viewed as a disposal site for waste, with many estimates suggesting that mismanaged waste on land is largely responsible for ocean litter (Vanapalli et al., 2021). The detection of plastic pollution in the marine environment and its increase in abundance has highlighted the adverse anthropogenic impact on the environment. The persistence of plastic debris adversely affects wildlife by presenting an environmental hazard, which has consequential effects on global economies, biodiversity loss, ecosystem function and human health (Hartmann et al., 2019; Hidalgo-ruz et al., 2012).

Mismanaged plastic waste leaked into the environment from landfills, littering, fishing and shipping activities has led to marine ecosystems acting as a sink for plastic debris, such as the oceanic gyres of the Great Pacific Garbage Patch (Petersen and Hubbart, 2021). Rivers and

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estuaries in urban settings are major conduits and collectively account for a large proportion of plastics entering the oceans (Naidoo and Glassom, 2019). Plastics can persist in marine and coastal environments due to their long degradation times (Sparks and Immelman, 2020). Over time, the large volume of plastic accumulating in the environment breaks down into smaller polymer fragments known as microplastics that are described with average sizes between 1 μm and 5 mm (Zhu et al., 2021). They are present in a variety of colours, chemical compositions, and morphologies, such as beads, films, fragments and fibres, each with its own toxicological impact (Miller et al., 2021). Microplastics are used in industrial processes, personal care- and domestic cleaning-products, and have been found to be present in seafood, sea salt, air, and drinking water (Dwiyitno et al., 2021; Zhang et al., 2020). The contamination of global environments by microplastics has gained widespread attention, with increased efforts attempting to understand the fate and risk of microplastics in different environments (Pakhomova et al., 2022).

South Africa is one of the largest contributors of plastic waste in the world. However, the quantitative data available for environmental microplastic pollution is relatively limited (Nel and Froneman, 2015). Few studies have investigated the occurrence of microplastics, their abundances, and polymer types in aquatic ecosystems (Naidoo and Glassom, 2019; Nel et al., 2018; Preston-whyte et al., 2021; Ramaremisa et al., 2022; Saad et al., 2022). While all these studies are recent, some investigations were performed in surface water flowing in the inland regions of the country (Nel et al., 2018; Ramaremisa et al., 2022; Saad et al., 2022). Considering its coastline of 3 400 km, and major cities along the coast, it is necessary to provide a robust assessment on the occurrence of microplastics in the coastal areas. In addition, there is a need to understand the current abundances and potential sources of microplastic pollution within the South African context, where coastal areas are tourist destination hotspots, with available seafood becoming the source of income for many residents and affordable food for several households. Therefore, investigating the occurrence of microplastics in coastal waters is important in order to implement measures to prevent anthropogenic litter entering the aquatic ecosystems (Verster et al., 2017).

Durban Bay in the metropolitan city of Durban (located in the province of KwaZulu-Natal, South Africa) was selected as a study site. This was necessary due to the dense populations surrounding the Durban harbour, and the amount of supporting infrastructure such as roads, wastewater treatment plants (WWTPs), stormwater drains and diverse industrial activities occurring within the vicinity of the study site. It was expected that a combination of all of these factors was likely to lead to multiple sources of microplastic pollution for these areas, making them interesting ecosystems to investigate. The situation worsened by climate change related issues like increased frequency of flash floods in the area that washes down uncollected solid waste from mostly hilly areas to down-streams and later the harbour. In addition, the Durban harbour act as a sink of many contaminants such as metals and organic chemicals introduced into the surface water through various activities. Notably, is the contribution of waterways which carry various substances from industries and WWTPs. For example, several chemicals including various classes of pharmaceuticals have been detected in the WWTP effluents which discharge their treated wastewater into rivers flowing to the Durban harbour (Hlengwa and Mahlambi, 2020; Moodley et al., 2015). Furthermore, there is always visible plastic litter around the harbour, in addition, to the metals and organics that have been previously found present in Durban harbour (Adeleke et al., 2020; La Guardia et al., 2013). Therefore, the aim of this study was to provide a baseline description for the potential inputs, abundance, and spatial distributions of microplastics in Durban Bay. Furthermore, the present study provide crucial information which highlights the vulnerability of the Durban harbour through its contamination due to human activities. This was necessary to fill the knowledge gaps, and to provide comparisons of spatial patterns with findings from previous investigations conducted in South Africa and abroad. This information is essential for determining whether the microplastic pollution in the selected study area is a significant problem which should be considered as isolated case for remedial action.

2. Materials and methods

2.1. Study area

An assessment of microplastic abundance, its key potential sources, and polymer types was carried out by analysing microplastics in sediment and surface water samples collected in Durban Bay. Durban Bay is an estuarine embayment in which the largest container handling port in sub-Saharan Africa is situated (Adeleke et al., 2020; Preston-whyte et al., 2021; Vogt et al., 2019). The Bay is located on the eastern coast of South Africa (29° 52′ S; 31° 04′ E), in the country's third largest metropolitan city of Durban, and connects to the Indian Ocean. Durban is characterised by a humid subtropical climate, with an average annual rainfall of 1 054 mm (Moodley et al., 2015). Durban is a highly urbanised, major industrial and economic hub administered by the eThekwini Municipality (Adeleke et al., 2020; Naidoo and Glassom, 2019). The population is approximately 3.5 million people, with many inhabitants occupying informal settlements that are densely populated and lacking basic necessities such as piped water, basic health care, and sanitation and waste collection services (Vogt et al., 2018).

Three rivers and several surface runoff canals with industrialised and urbanised catchments flow into Durban Bay, including Bayhead Canal and the Umhlatuzana, Umbilo and Amanzimnyama rivers (Moodley et al., 2015; Preston-whyte et al., 2021). Potential sources of pollution from shipping activities in Durban Bay include the maintenance of vessels, loading and offloading of bulk and breakbulk cargo, automotive carriers, cruise ships, and smaller fishing and recreational boats (Preston-whyte et al., 2021). Therefore, microplastic pollution can be derived from the activities and land uses typical of the area around Durban Bay (Adeleke et al., 2020).

2.2. Sample collection

Microplastics were sampled in surface water and sediments from 15 sites (Table 1) in Durban Bay in August 2020. Microplastics in the water column at each site were sampled by towing a conical plankton net (50 μm mesh size, 0.5 m opening size, 1 m length) alongside a small vessel at about 2 knots for approximately 50 m. A calibrated flowmeter (Hydrobios mechanical flow meter) was fixed in the centre of the mouth of the net and used to calculate the volume of water sampled. Approximately 10,000–20,000 L of water was sampled along each transect. At the end of each tow the net was held upright, and material was washed to the cod end using water pumped from the ambient through a hose with a spray fitting. Water was only sprayed onto the net from the outside. The retained material was transferred to 500 mL glass jars and preserved by adding filtered 100% ethanol.

Microplastics in sediments were sampled using a van Veen grab. The sediments from two grabs were transferred to a glass bowl, homogenised using a stainless-steel spoon, and about 150 g was then transferred to an amber glass jar.

2.3. Pre-treatment of sediment samples

Sediment samples were frozen until processing and analysis. The samples were freeze-dried for approximately 48 hours to obtain the dry weights and to standardise differences in moisture content between samples. Approximately, 100 g of dry sediment was weighed into triplicate subsamples and transferred into 50 mL centrifuge tubes. The weight of each subsample was recorded. All of the equipment and glassware were prewashed with filtered reverse osmosis water three times prior to use during sampling and sample processing to avoid

Table 1
Description of the selected study sites within the Durban Bay, with their associated anthropogenic activities nearby (See also Fig. 1).

Sampling Site	GPS Coordinates		Water Depth (m)	Location	Nearby Activity
	Latitude	Longitude			
Durban Bay 1	-29.903863	31.008163	1.5	Silt Canal	River inflow; Yacht Club
Durban Bay 2	-29.898478	31.004679	3	Silt Canal	River inflow
Durban Bay 3	-29.892686	31.006605	7	Silt Canal	River inflow
Durban Bay 4	-29.885709	31.006780	7	Congella Basin	Shipping activity; Stormwater Drains, Vessel repair and maintenance
Durban Bay 5	-29.879045	31.007044	14	Maydon Channel	Shipping Activity; Stormwater Drains
Durban Bay 6	-29.871302	31.014386	16	Maydon Channel	Shipping Activity; Stormwater Drains
Durban Bay 7	-29.869218	31.027294	14	Esplanade Channel	Shipping Activity
Durban Bay 8	-29.874960	31.018762	13	Harbour	Shipping Activity
Durban Bay 9	-29.881358	31.025232	13	Container Terminal Pier 2	Container Terminal
Durban Bay 10	-29.879390	31.033074	13	Durban Container Terminal Pier 1	Container Terminal
Durban Bay 11	-29.880742	31.042174	12	Island View	Naval Station
Durban Bay 12	-29.874669	31.048850	12	Durban Point Terminal	Mahatma Gandhi Sewage Pump Station
Durban Bay 13	-29.874823	31.041952	12	Durban Point Terminal	Mahatma Gandhi Sewage Pump Station
Durban Bay 14	-29.865470	31.032881	13	T Jetty & Cato Creek	Quayside Road
Durban Bay 15	-29.864234	31.024148	5	Boatman's Road	Stormwater Drain; Yacht Clubs; Laundry Service

contamination.

2.4. Sample processing

2.4.1. Sediment samples

Sediment samples were processed according to the method described by (Lusher et al., 2015). Microplastics were separated from the sediment using a flotation process, followed by vacuum filtration of the supernatant. The separation of microplastics and inorganics was performed using a concentrated salt solution of sodium iodide. This was done by mixing the dry sediments with a filtered solution of sodium iodide in 50 mL centrifuge tubes, followed by vigorously shaking the mixture to separate microplastics from the sediment matrix. The mixture was left to settle for a 24-hour period to allow for the less dense microplastics to float on the top of hypersaline solution, while the sediment settled towards the bottom, resulting in recovery of microplastics (Hidalgo-ruz et al., 2012). Thereafter, the supernatant with the floating microplastic particles was decanted and vacuum filtered using Whatman® glass microfiber filters, Grade GF/A (1.6 µm pore size, 47 mm diameter) (Cytiva Danaher Group, Buckinghamshire, United Kingdom). To increase the recovery of microplastics, the same sediment sample was subjected to a second round of density separation and extraction. After the filtration process, the individual Whatman® glass microfiber filters were transferred into respective Petri dishes and allowed to airdry, prior to visual analysis and microplastic identification. Method blanks were incorporated to account for any contamination using the extraction procedure outlined for microplastics, however in the absence of sediment sample. In addition, the procedural blanks were incorporated for every five samples processed during each step of sample processing to account for any laboratory contamination that could occur during the extraction processes.

2.4.2. Water samples

Water samples were vacuum filtered over Whatman® glass microfiber filters, Grade GF/A (1.6 µm pore size, 47 mm diameter) (Cytiva Danaher Group, Buckinghamshire, United Kingdom) to retain microplastics and other debris. The sample container and filter funnel were rinsed with filtered reverse osmosis water to remove remaining adhered particles. Method blanks were incorporated to account for any experimental contamination whereby the Whatman® glass microfiber filter was rinsed with filtered water. The Whatman® glass microfiber filters were immediately transferred to clean Petri dishes and covered, and then allowed to air dry. In addition, the procedural blanks were incorporated for every five samples processed during each step of sample processing to account for any laboratory contamination that could occur during the extraction processes.

2.4.3. Removal of organic matter

Water and sediment samples, with rich organic matter content in their matrix, required an additional sample processing step to efficiently extract the microplastics. In this case, visual inspection of the samples was used to select turbid samples influenced by a result of undissolved organic matter, aquatic organisms such as algae that were expected to clog the pores of the Whatman® glass microfiber filters (1.6 µm pore size, 47 mm diameter). Such samples were subjected to digestion for removal of organic matter which improved the filtration process. Digestion was achieved by performing chemical oxidation in conical flasks using hydrogen peroxide at 40 °C. The conical flasks were covered with foil upon the addition of hydrogen peroxide and left for 24 hours to digest biological material which could hinder the detection of microplastics during characterisation. Once digested, water samples were filtered using Whatman® glass microfiber filters (1.6 µm pore size, 47 mm diameter). The contents of the Whatman® glass microfiber filters were rinsed with reverse osmosis water and transferred into Petri dishes. Upon the completion of organic matter removal, sediments were washed with filtered water and the water was vacuum filtered onto Whatman® glass microfiber filter (1.6 µm pore size, 47 mm diameter). The Whatman® glass microfiber filter with microplastics was immediately transferred to a Petri dish and covered for drying prior to visual identification.

2.5. Microplastic visual identification

The visual inspection of all Whatman® glass microfiber filters from samples and blanks was carried out to quantify and sort the suspected microplastics based on their properties. This was done by viewing the particles retained on Whatman® glass microfiber filter under a stereomicroscope equipped with digital camera attachment to separate suspected microplastics from other materials. Identification of microplastics was based on certain characteristics as stated in the step-by-step guide established by (Hidalgo-ruz et al., 2012). A particle was classified as a potential microplastic if it met the following criteria; 1) no

cellular or organic structures were observed in the morphology; 2) fibres had to be evenly thick throughout their length and not tapered towards the ends; 3) fibres had to be a single colour and transparent fibres that had a glass-like texture were excluded; 4) if a particle broke when pressure was applied using forceps, it was not included; 5) fibres were not segmented and did not appear as twisted flat ribbons.

Suspected microplastics and their characteristics were analysed and recorded according to their colour, dimension (longest and shortest axes were measured), and morphology classes from visual sorting. Morphology identification was based on the shape characteristics of the microplastic particles and were grouped into fragments (small irregular pieces), pellets (spherical items), films (thin layer) or fibres (elongated). Particles identified as potential microplastics were photographed using AxioVision SE64 Rel. 4.9.1 Software on a desktop computer. The particles were placed together on the Whatman® glass microfiber filter using forceps to allow for easier tracing during spectroscopic chemical characterisation.

2.6. Polymer identification

A Horiba LabRAM HR Raman spectrometer (Horiba Jobin Yvon, Kyoto, Japan) was used to confirm the polymer composition of visually identified microparticles. The equipment was attached to an Olympus BX41 microscope (Olympus Inspection Solutions (Evident), Waltham, Massachusetts, USA) for microplastic measurements. The Raman spectrometer was equipped with gratings ruled at 600 lines per mm and a liquid nitrogen-cooled charge-coupled device detector. In this case, an Argon laser with wavelength of 785 nm was used to cause a Raman-effect. A silicon sample was used as a reference spectrum. The equipment was calibrated during each day of microplastic measurements using a silicon wafer and analysing the first phonon band of silicon at 520.7 cm^{-1}. A 514.5 nm argon ion laser was used for spectra acquisition. Raman spectra were recorded in the wavenumber range of 100–3500 cm^{-1}. Due to high background fluorescence in some microplastics, particles were subjected to photobleaching for 5–60 s before acquisition depending on the intensity of the background fluorescence. Raman spectra were compared to a library of spectra for microplastics (SLOPP-E library) to confirm a polymer match. LabSpec 6 Spectroscopy Suite Software (Horiba Jobin Yvon, Japan) was used to operate the Raman microspectrometer and do background subtraction of the sample spectra.

2.7. Contamination mitigation measures

Strict protocols were followed during sample collection, transportation, and processing in the laboratory to minimise contamination. Microplastic extractions and analyses were conducted in a laboratory dedicated to microplastic sample processing. All samples were processed in a laminar airflow cabinet to prevent airborne contamination. All surfaces including the laminar airflow cabinet, and microscope were wiped down with filtered water daily before use to remove dust particles. The glassware and labware used for sampling and sample processing were rinsed three times using 0.22 μm filtered reverse osmosis water prior to use and in-between samples. Samples were kept covered with aluminium foil and metal lids when not in use to avoid exposure to airborne particles in the laboratory. Glass and metal equipment were used throughout the study while minimizing the usage of plastic-based equipment. Synthetic garments were avoided during the analysis, and only natural fibre cotton clothing were used to mitigate the risk of sample contamination. Reagents used during sample processing were vacuum filtered on Whatmann glass fibre filters prior to use. Procedural blanks were incorporated for every five samples processed during each step of sample processing to account for any laboratory contamination that could occur during the extraction processes. The microplastic particles from the blanks were analysed and corrected in the microplastic counts from environmental samples. A total of three black and two blue microfibres were detected across all the blanks for surface water samples, whereas no particles were detected in the blanks incorporated for sediment samples. Sample correction was applied by subtracting five microfibres of the corresponding colours from surface water samples and all totals presented in the results are corrected values. Blank samples were done by processing deionised water to test any contamination coming from the glassware used and no evidence of contamination was obtained.

2.8. Statistical analysis

Statistical analyses were conducted in Excel and R Studio statistical software. After plastic particle counts and sample weights were standardised, a one-way ANOVA test was conducted to determine whether differences in the spatial abundances in sediment samples between stations were statistically significant. The significance threshold was $\alpha = 0.05$. A Post-hoc Tukey HSD was applied to determine which sites in Durban Bay had abundance differences that were statistically significant.

3. Results and discussion

3.1. Abundance and spatial variations of microplastics in Durban Bay

3.1.1. Surface water

Microplastics were detected in all surface water samples, at concentrations between 4.27 and 80.72 particles m^{-3} (average concentration = 18.82 ± 18.65 particles m^{-3}) (Fig. 1a). The greatest abundance was at Site 1 in the Silt Canal, near the inflow of the Amanzimnyama River. Microplastic abundance was also relatively high at Site 2 in the Silt Canal, off the inflow of the Umbilo/ Umhlatuzana Rivers. Microplastic abundance at other sites showed no pronounced spatial trend. There is little doubt that the rivers, various canals and stormwater discharge points are sources of the plastics. This is because the extremely large volumes of plastic and other solid waste enter the Durban Bay during periods of high rainfall. The rivers flowing into the Durban Bay are recipients of various WWTP effluents such as those from Umhlathuzana and Umbilo WWTPs which have been reported to contain several water contaminants (Madikizela and Chimuka, 2017a, 2017b). The water quality from these WWTPs is likely to influence the state of the river water which has an impact on the water quality in the Durban Bay. In this context, the spatial distribution of microplastics in site 1 may be due to the proximity of the river inlets into the harbour and the contributions of the yacht clubs. However, this information can be verified in future through the monitoring of microplastics in river water entering the harbour, thus enabling studies on source apportionment. Sites 2–4 (with high levels of microplastics) are situated within the Bayhead canal and near the yacht clubs.

Sites 5 and 6 have potential microplastic inputs from surrounding stormwater drains. Sites 11, 12 and 14 have relatively lower abundances, whereas site 13 has a higher abundance of microplastics due to the site's proximity to the Mahatma Gandhi sewage pump station. This sewer pump station is one of the largest pump stations in KwaZulu-Natal, and transfers sewage encompassing the Durban central business district, Berea and neighbouring areas of the harbour to a treatment system towards the seaward border of the Bluff. Sites 9 and 10 are located close by to a container terminal, however site 10 has comparatively higher microplastic abundance. This may be due to site 9 being situated within an enclosed space preventing the migration of microplastics to other areas. Site 15 is located nearby to stormwater drains, yacht clubs and a laundry service which are potential inputs leading to the high microplastic abundances observed. This is expected as stormwater has been found to be a distinctive transport route of microplastics contributing approximately 140 times more micro-debris than wastewater (Zhu et al., 2021).

Sites 7 and 8 located in the centre of the harbour had relatively

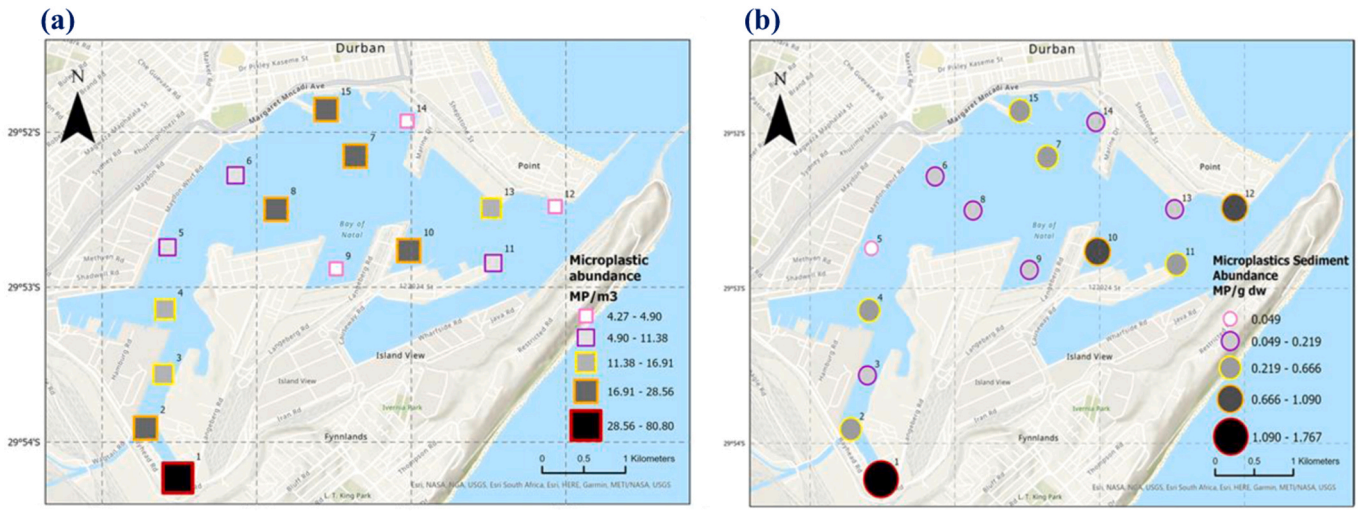


Fig. 1. Maps depicting microplastic abundance (particles/m^3) in surface water (a) and sediments (b).

higher microplastic abundances. This may be attributed to heightened shipping activity which is one of the main contributors to the amount of pollution in the study area, and may also lead to the transport, deposition and redeposition of microplastics (Vanapalli et al., 2021). Shipping activity in conjunction with other factors such as the intensity of winds, density and morphology of microplastics, can also transport and deposit microplastics to areas far from their disposal sites (Vanapalli et al., 2021). Variations in microplastic abundance may be influenced by the sampling depth. Hence, the highest microplastic abundances have been observed in shallower waters with low water velocity (Gerolin et al., 2020). The sites in Durban Bay with shallow waters (< 10 m) consisted of sites 1–4, and site 15 which consisted of relatively higher microplastic abundances.

3.1.2. *Sediments*

Microplastics were detected in the sediments at all sites, at an average abundance of 0.447 particles g^{-1} and a range of 0.039 particles g^{-1} to 1.76 particles g^{-1} (Fig. 1b). Similar to surface water, the highest microplastic abundance was at Site 1 in the Silt Canal. Microplastic abundance at other sites showed no pronounced spatial trend.

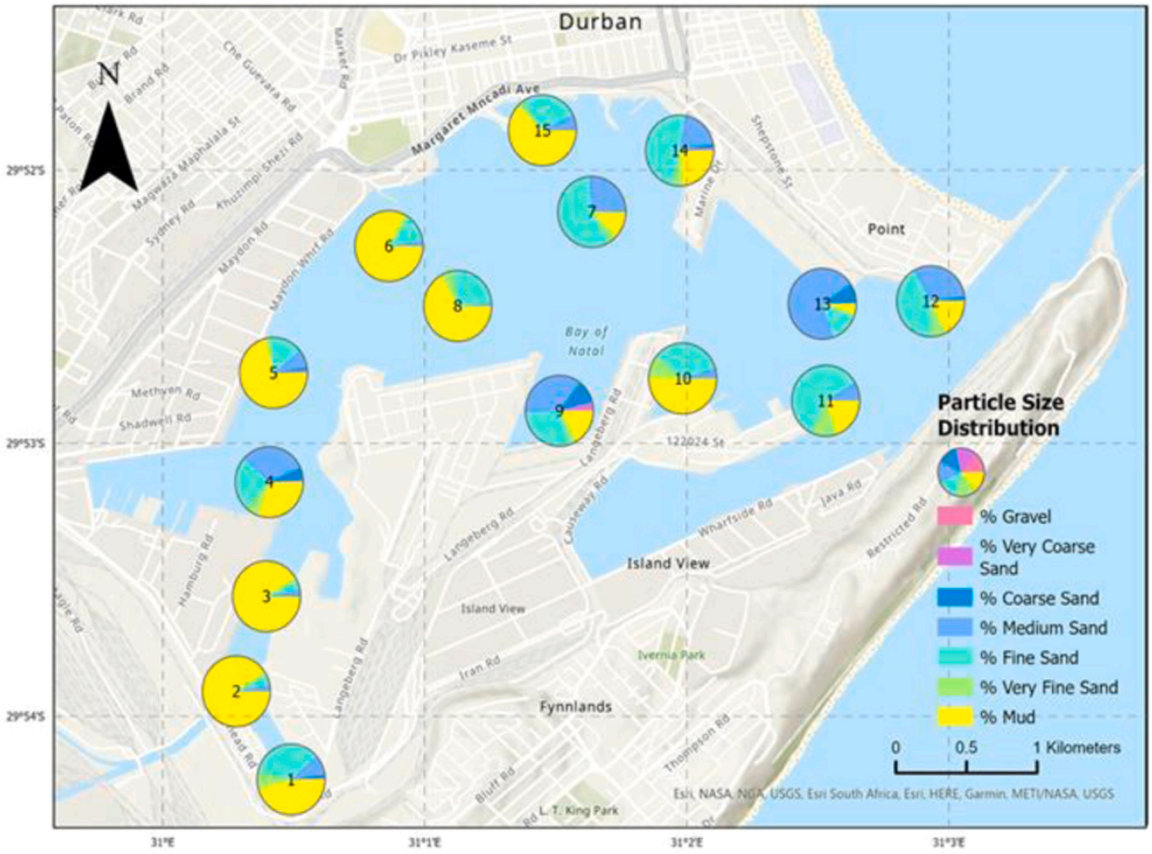


Fig. 2. Map depicting particle size distribution of microplastics in sediments at each study site.

Fig. 2 provides the grain size composition of sediments at each site. The relationship between mud content and microplastic levels has not been established, however, selected studies have shown a direct correlation between the sediment grain size and the percentage content of mud i.e. sediments with a high mud fraction were found to contain relatively higher abundance of plastics (Pagter et al., 2018). In this study, it was observed that the contribution of mud to the bulk mass of sediments varied widely, from 4% to 93%. The sediments at most sites closest to the river inflows were dominated by mud. Particle size distribution analysis from the collected samples indicated that sediments with largest mud composition (>50%) are from sites 3, 2, 6, 5, 8, 15 and 10 (listed from highest mud composition to lowest). Microplastic abundance across these sites do not show trends related to mud composition. Therefore, there is no indication that sediment composition is an influencing variable to the abundance and accumulation of microplastics in Durban Bay. A one-way ANOVA analysis showed significant differences between microplastic abundances across the different sampling sites ($p = 0.000119$, $\alpha = 0.05$). A Post – HOC Tukey test also revealed site differences.

3.2. Morphology

The results obtained for morphology of microplastics in surface water and sediments are shown in Fig. 3. A total of 5 578 particles (4 366 in surface water and 1 212 in sediments) were identified across the sites. The microplastics comprised fragments, fibres, pellets, and films. Fibres were dominant in surface water (75.68%), followed by fragments (19.84%), films (3.28%), and pellets (1.21%). In sediments, fragments constituted the highest proportion (58.25%), followed by fibres (33.58%), films (6.02%), and pellets (2.15%). These results are in alignment with findings of a previous study, which showed that fragments are commonly detected in sediments (Matsuguma et al., 2017). Films and fibres are lightweight and can also be carried into the harbour by wind. Discarded fishing gear and angling gear is a potential source of secondary microplastics such as fibres and fragments.

The morphology compositions of microplastics present varied across different sampled sites (Fig. 3). While fibres were most found in surface water samples (Fig. 3(a)), site 1 had a greater proportion of fragments due to the site's proximity to the river inflows. In sediments, both fibres and fragments were dominant (Fig. 3(b)). Marginalised and impoverished communities are especially susceptible to the repercussions of plastic littering and build-up, which include the blockage of waterways and urban drainage systems, causing urban flooding events. Durban Bay is often forced to close after a heavy rainfall event due to the build-up of substantial amounts of plastic debris and other refuse materials, which may potentially result in damages to ships causing additional clean-up and repair costs. Urban stormwater inlets and treated wastewater have been found to be a major source of fibres (Busch et al., 2023; Werbowski et al., 2021), whereas river pathways have been found to be major sources of fragments (Tibbetts et al., 2018). However. the influx of plastic debris during periodic rainfalls may result in stormwater drains comprising of a larger proportion of fragments.

The widespread presence of microfibres in surface water samples may be attributed to the breakdown of commercial fishing nets and textile fibres from domestic wastewater, carried into the harbour from stormwater drains and river inflows. These fibres may arise from the disintegration of larger materials that are carried over large distances, or by local vessel activity within the harbour. Particle composition of surface water samples were high for fibres across all sites, while sediment samples had high microfibre compositions (> 50% fibre composition) at sites 3, 5, 6 and 13. These sites are all associated with proximity to storm water outfalls in the harbour, with sites 3, 5, 6 being closest to the area of the harbour where stormwater drains are clustered together. Site 13 is exposed to the stormwater drain and the Mahatma Gandhi WWTP suggesting input from wastewater is also a potential source of the high amounts of fibres detected in sediment at site 13.

The high proportion of fragments present in sediment samples may be the result of degradation due to abrasion and weathering of larger plastic debris. The observed results are indicative of microplastics most likely being a product of the fragmentation of larger plastic debris, such as fishing equipment, and inputs from stormwater and river inflows. The larger plastic debris undergo fragmentation during their transportation over long distances in riverine systems from their different point and non-point sources (Vanapalli et al., 2021).

The presence of pellets may be indicative of microbeads from cosmetic products and higher proportions were observed at sites nearest to rivers and stormwater drains. Pellets may be introduced through the unintentional release from dry docks or effluent. Films are largely a result of mismanaged single-use plastics that are easily transported via air currents and river flows (Vanapalli et al., 2021). Films constituted a large portion of plastics in surface water samples; these plastics are dominant in the water column due to their low density and are likely sourced from plastic packaging which is in high demand in South Africa.

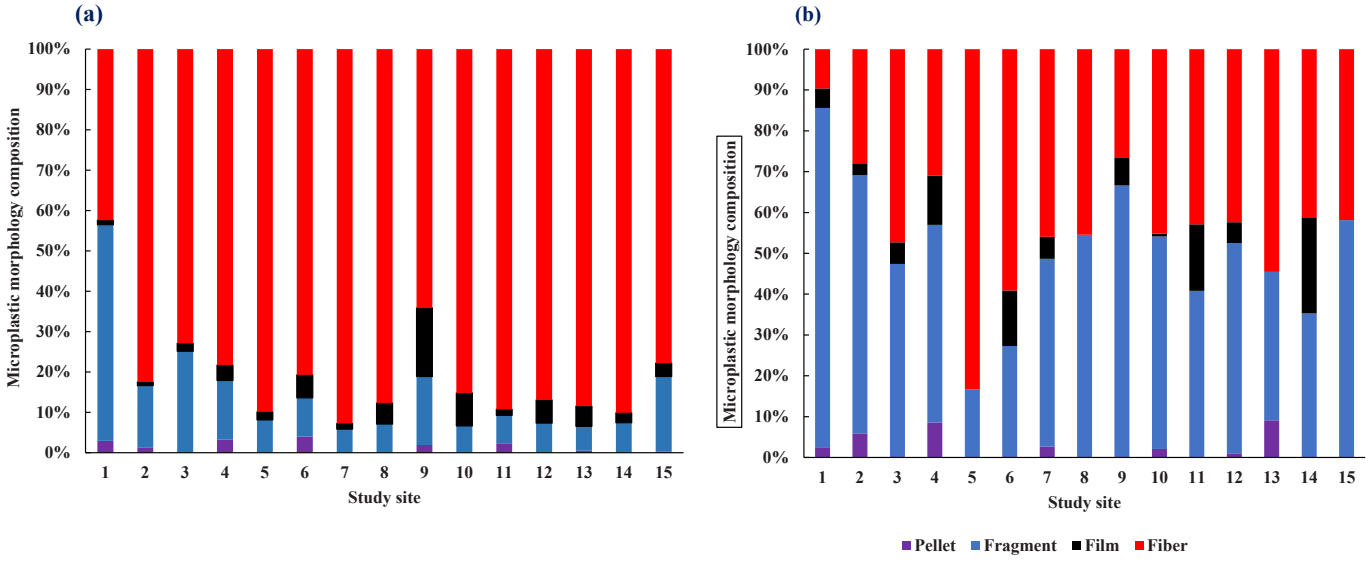


Fig. 3. Morphology composition (pellets, fragments, films and fibres) of microplastics observed in surface water (a) and sediments (b).

3.3. Size distribution

Fig. 4 shows the size distribution of the identified microplastics in both surface water and sediments. The particle sizes of detected microplastics were ranging from 7.31 μm to 4992 μm. The average size of microplastic particles found in water samples was 1.63 ± 1.23 mm. In this case, the size distribution followed the order of fiber > fragment > film > pellet (Fig. 4(a)). Fig. 4 further shows that while the surface water consisted of predominantly fibres (Fig. 4(a)), the fragments were dominant in sediments followed by the fibers (Fig. 4(b). This means the fragments tend to sink to sediments, which retains microplastics more to the bay area. The high abundance of smaller microplastics (<2 mm) indicates that particles are likely to continually disintegrate into microscopic-scale particles over time. Particle size and density have been suggested as key factors contributing to the microplastic deposition process (Su et al., 2020).

The circularity of particle morphology varied inversely with particle size, whereby larger microdebris had more elongated shapes or irregular surfaces, comprising of fibres and fragments, while more circular particles were observed in the progressively smaller particle size ranges (<1 mm). The widespread presence of microplastic in surface waters heightens the probability of marine biota, which inhabit the same locale, being exposed to microplastic particles. The risks posed by plastics differs based on their size, notably, small-sized microplastics act as vectors of coexisting pollutants owing to their large surface area. Thus, smaller microplastics may pose heightened risks to filter feeding organisms. It is predicted that benthic organisms are likely to be exposed to microplastics, leading to the eventual uptake of the microplastics and transfer along trophic levels.

3.4. Colour composition

The type of microplastics in colour found in surface water and sediments is shown in Fig. 5. In this study, the colour of microplastics varied widely, ranging from neutral colours like black, to colours that stand out, such as red and pink (Fig. 5). The most commonly detected fragments were transparent (35.55%), followed by blue fragments (15.44%) which is in agreement with findings of a previous study (Bronzo et al., 2021). The importance of studying the colour composition of microplastics is associated with inferring the sources of contamination (Frias and Nash, 2019). Therefore, it was necessary to examine the colour composition of microplastics detected in the present study. This is despite the general view that the colour assignment of microplastics is not considered crucial, due to colour differentiation being subjective based on the individual analysing the particles and does not provide information to visual identification as a standalone variable. At the same time, colour assignment is considered as an important characteristic due to the fact that some aquatic species potentially ingest microplastics based on a colour preference behaviour (Frias and Nash, 2019).

3.5. Polymer composition

The polymer composition of selected microplastics found in Durban Bay was identified using Raman microscopy. In 45 suspected microplastic particles, polyethylene was the most abundant polymer type in sediments and surface water. Polymers identified in surface water consisted of polyethylene (46.67%), polyester (24.44%), polypropylene (13.33%), polystyrene (11.11%), and polyamide (4.44%). The same polymers were found in sediments, but with varying proportions. In this case, polyethylene was most common (52.38%), followed by polypropylene (23.81%), polyester (14.29%), polystyrene (7.14%), and polyamide (2.38%). This is similar to the results from other port environments, such as Kuantan port in Malaysia, where the same polymer compositions were reported (Khalik et al., 2018). In addition, a previous review on microplastics in the marine environment established that the most commonly identified polymers consisted of polyethylene, polypropylene, and polystyrene, which are frequently used for the purpose of packaging (Preston-whyte et al., 2021).

While it is difficult to pinpoint the exact sources of these polymers, they have a multitude of applications inclusive of textiles, packaging (plastic bags and bottles), fishing nets, rope and microbeads. The commercial dry dock facilities located near Bayhead may serve as a direct input of polystyrene and polyester from activities, involving ship repairs and maintenance. Polyester fibres from weathered rope discarded from fishing activities, and washing machine effluent, are also origins of microplastics commonly observed.

3.6. Comparisons to other studies

Durban Bay harbour is one of 16 estuaries in the eThekwini municipality. Previously conducted studies on five of these estuaries have found Durban Bay to contain the most concentrated amounts of microplastics, with their concentrations decreasing with increased distance away from the Durban metropolitan centre (Preston-whyte et al., 2021). Aquatic systems located in urbanised areas and subjected to vast anthropogenic activities, such as harbours, have been found to be

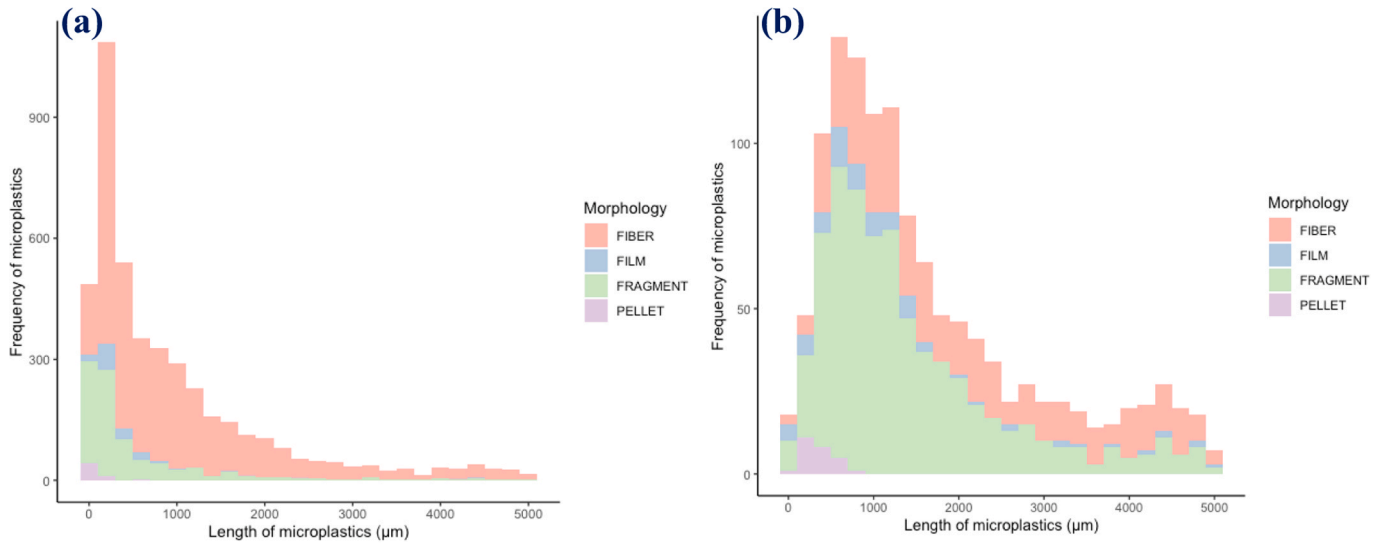


Fig. 4. Size distribution of microplastics in surface water (a) and sediments (b).

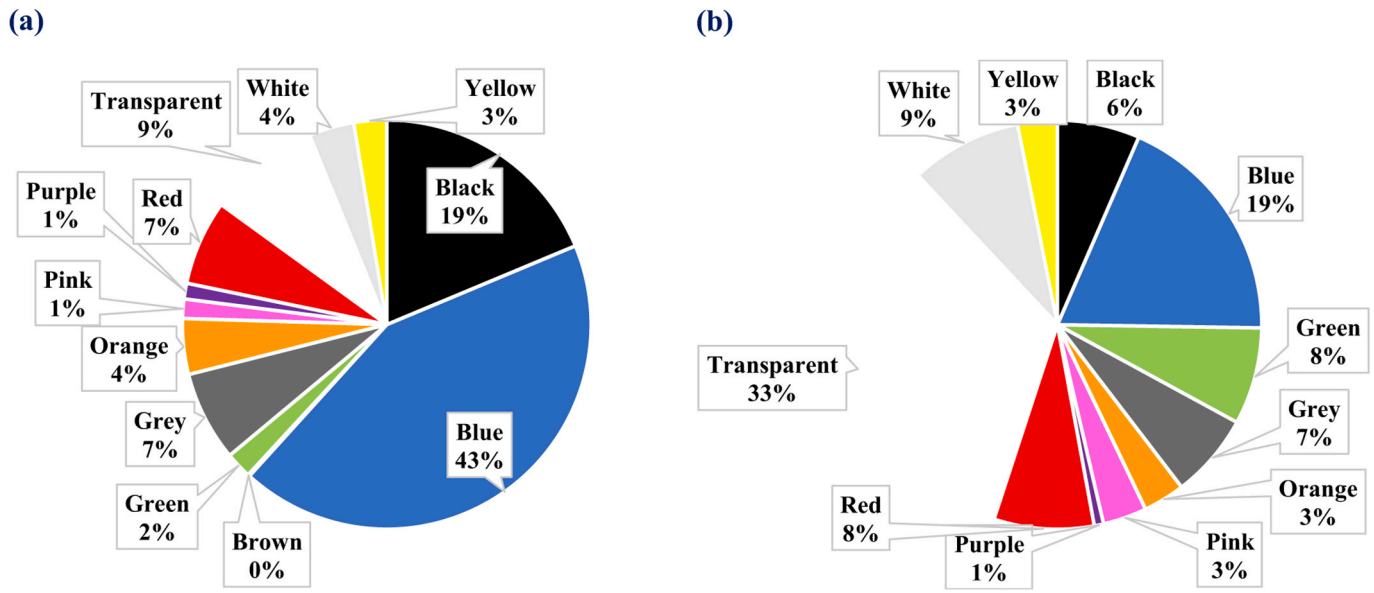


Fig. 5. Colour assignments for microplastics found in surface water (a) and sediments (b).

increasingly contaminated with microplastics, and act as their transport route entering the marine environment (Naidoo et al., 2020).

A detailed comparison of the amount of microplastics found in this study in relation to the quantities presented in other studies is given in Table. A previous study conducted within Durban Bay measured an average microplastic concentration in water and sediment samples of 7.03 ± 11.93 particles m^{-3} and 2400 ± 529 particles kg^{-1}, respectively (Naidoo et al., 2020). A different study reported an average abundance of microplastics in near surface water to be 99.14 ± 36.29 particles m^{-3} (Preston-whyte et al., 2021). The present study found microplastics in surface water samples with concentrations between 4.27 and 80.72 particles m^{-3}, while the amount in sediments had a maximum amount of 1.76 microplastics g^{-1}. Variations in these levels could be associated with episodic events with sampling conducted in different times. The occurrence of microplastics in these environmental samples is concerning as the Juvenile fish inhabiting mangroves in Durban Bay were found to consume significant quantities of microplastics, with a maximum of six particles observed in the fish (Naidoo et al., 2020). Ingested microplastic particles consisted predominantly of fibres and fragments, which are the most commonly detected microplastics within this study (Preston-whyte et al., 2021). The high abundance of microplastics detected in Durban Bay suggests that biota is exposed to these substances, thus, posing health risks. More concerning, the sediments in Durban Bay were found to contain higher concentrations of microplastics relative to other estuarine ports in South Africa (Sparks et al., 2021). Table 2.

Table 2
Comparison of microplastic concentrations found in water and sediments.

Study site	Reported microplastic concentration		Reference
	Water (particles m^{-3})	Sediments (particles g^{-1})	
Haikou Bay, China	0.26–0.84	0.013–0.34	(Qi et al., 2020)
Banten Bay, Indonesia	-	0.10–0.43	(Falahudin et al., 2020)
Hangzhou Bay, China	-	0.04–0.48	(Li et al., 2020)
Gorgan Bay, Caspian Sea	-	0.08–0.74	(Bagheri et al., 2020)
Bandon Bay, Gulf of Thailand	0.04–0.33	-	(Ruangpanupan et al., 2022)
Mediterranean Bay (Al Hoceima, Morocco)	1–15	-	(BOUADIL et al., 2024)
Durban Bay, South Africa	42–145	2.4–112	(Preston-whyte et al., 2021)
Durban Bay, South Africa	4.27–80.72	0.04–1.76	This study

3.7. Consequence management

The findings of the present study highlight the need for managing stormwater into the harbour in order to improve the water quality in the Bay. Ensuring adequate stormwater management upstream and actual solid waste management are essential as stormwater outfalls are major contributors of contaminants introduced into the harbour. Strategies need to be implemented to control the pollution of the harbour by litter and other wastes caried in by stormwater from the surrounding areas. The current practise for elimination of litter around the Durban Bay is based on the collection and removal of such solids by Durban solid waste division which forms part of eThekwini Municipality. This approach does not completely eliminate the litter as the collection and removal are not performed routinely. In addition, this is only done for unwanted solids next to the waterbodies, resulting in overlooking the potential strategies for the removal of litter and its by-products already present in water.

Catchment management interventions are required for point and diffuse sources of pollution which include gross pollutant traps and sediment traps for stormwater treatment interventions. The enforcement of illegal pollution incidents and implementing GIS-based system of pollution sources for continuous monitoring is also required to prevent the continuous contamination of the harbour. This is important as the Durban Bay Management acknowledged that its ecosystem is degrading with human activities within its boundaries identified to have an effect on physical, abiotic and biotic elements of the system. In addition, the National Guideline for the discharge of effluent from land-based sources into coastal waters (2014), South African Water Quality Guidelines for Coastal Marine Waters (2012); National Policy for Pollution and Waste Management are relevant to water quality (National Department of Environmental Affairs, 2016). However, without a continuous monitoring of the water quality within the Durban Bay, it becomes impossible to ensure that such policies are implemented. Therefore, the results of this study are believed to be able to act as a catalyst towards the implementation of suitable solutions to curb pollution within the Durban Bay.

Implementations of these regulations will aid in managing the biophysical environment and create opportunities for restoring the existing habitat and prevent the loss of sensitive habitat and the reduction in biodiversity. Managing development activities in proximity to sensitive areas will also prevent the loss of ecosystem goods and services, and the pollution of marine and terrestrial environments. Long term monitoring and management will aid with potentially controlling the microplastic particles in harbours and prevent them from entering other environments such as marine ecosystems and the food web.

The pollution of water, air, land, and sediment leads to adverse health or nuisance effects to residents who live around the harbour and people working in or visiting the harbour. It is necessary to manage water quality impacts and ensure that all possible causes of pollution are mitigated as far as possible to minimise impacts to the surrounding anthropogenic activities. Remediating the contaminated areas earmarked for plastic pollution entry points will aid with minimising the contamination of freshwater resources and sediments.

4. Conclusion

The present study reports the occurrence and distribution of microplastics in surface water and sediments within the Durban Bay, South Africa. The occurrence of microplastics in the investigated study sites is a concern as the contamination of harbours places continual risks to the surrounding aquatic environments. Microplastic pollution was observed in all 15 sampled sites across the Durban Bay harbour with varying concentrations in surface water and sediments. The relatively higher microplastic concentrations were observed towards the areas of the harbour located adjacent to river inflows. This points-out to the rivers as potential major contributors of microplastic contamination in the Durban Bay. The most commonly detected polymer type for surface water and sediments was polyethylene. The results of the present study give an indication to the sources of microplastic pollution which include shipping activities, river inflows and stormwater outfalls. The effective remediation of polluted sediments is necessary for the preservation of the environment and the health of biota. Accurate identification of the sources of microplastics will aid in the future management of the harbour to mitigate potential long-term risks associated with the accumulation of microplastics and the potential transport of the particles through biota and dredging activities.

CRediT authorship contribution statement

Luke Chimuka: Conceptualization, Project administration, Supervision, Validation, Writing – review & editing. **Brent Newman:** Data curation, Conceptualization, Investigation, Methodology, Resources, Writing – review & editing. **Kuria Ndungu:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Lawrence Madikizela:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Heidi Richards:** Writing – review & editing, Supervision, Conceptualization. **Dingambari Latcheman:** Writing – original draft, Methodology, Investigation, Formal analysis.

Declaration of Competing Interest

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

Data availability

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

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