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Microplastic occurrence and fate in the South African environment: a review

Ntebogeng Sharon Mokgalaka-Fleischmann[1], Funzani Asnath Melato[1], Khathutshelo Netshiongolwe[1], Oisaemi Uduagele Izevbekhai[2], Sello Presly Lepule[1], Kgomotso Motsepe[1] and Joshua Nosa Edokpayi[3*]

Abstract

This review examines the occurrence and fate of microplastics (MPs) in freshwater, marine, and terrestrial environments in South Africa. MPs were found in Tshwane and Johannesburg in drinking water samples, with concentrations as high as 0.189 particles/L. Concentrations in freshwater bodies were greater, sometimes reaching 0.33–56 particles/L. MP levels in marine sediments were greater than many worldwide averages, particularly along the southeast coast (up to 45,867 particles/kg) and the MP levels in air were 1–5 particles/m^3. These values are in line with figures around the globe which stand at 0.1–10 particles/L, and 0.3–10 particles/m^3 for water, and air respectively. Low-density PE, PP, and PE-HD were the most prevalent polymers identified. Although there is little data, inappropriate disposal of waste is a major cause of soil contamination, which is a serious concern. The study highlights how important it is to conduct more research to close knowledge gaps, especially regarding MPs in groundwater and their impact on human health. The findings emphasise the necessity of improved wastewater treatment technologies, public awareness initiatives, and stronger laws governing single-use plastics. Standardizing MPs detection techniques, improving our knowledge of MPs fate and transport, and estimating the effects of MPs exposure to human health should be the main goals for future research. Effective cooperation between researchers, legislators, and industry is necessary for mitigation initiatives to be successful.

Keywords Freshwater, Marine water, Terrestrial environment, Microplastic fate and transport

Introduction

Microplastic (MP) pollution has emerged as a significant global environmental concern. In South Africa, rapid urbanization, population growth, and inadequate infrastructure exacerbate the issue, threatening aquatic ecosystems and vulnerable communities (Yakubu et al., 2024). The prevalence of MPs in soil, water, and biota is driven by challenges common to many African countries. These include improper solid waste disposal, inadequate wastewater treatment systems, and weak enforcement of environmental regulations (Moto et al., 2024). For instance, research has indicated that urban and industrial activity close to informal settlements are the sources of the substantial MP contamination found in South Africa's freshwater systems, including the Vaal River (Saad et al. 2024). Additionally, the region's socioeconomic disparities and infrastructure limitations necessitate targeted interventions. Addressing these challenges through strengthened regional regulations and improved waste management systems is crucial for sustainable environmental management and safeguarding public health (Perkumienė et al. 2023).

MPs in the environment are classified into two main categories, primary and secondary, based on their origins. Primary MPs are intentionally manufactured and

*Correspondence:
Joshua Nosa Edokpayi
Joshua.Edokpayi@univen.ac.za
[1] Faculty of Science, Department of Chemistry, Tshwane University of Technology, Private Bag X680, Pretoria 0001, South Africa
[2] North Hertfordshire College, Stevenage SG1 1LA, UK
[3] Water and Environmental Management Research Unit, Faculty of Science, Engineering and Agriculture, University of Venda, Thohoyandou, South Africa

added to products like cosmetics, including exfoliating beads (Scudo et al. 2017). Secondary MPs are produced when larger plastic items, such as bottles, break down due to exposure to UV light and various natural processes (Rios et al. 2007; Scudo et al. 2017). Additionally, MPs can result from the unintentional wear and tear of plastic materials and their degradation, as well as from the bottom ash produced during incineration (Yang et al. 2021).

The Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (JGESAMP) in 2016 defined MPs as plastic particles with diameters ranging from 1 μm to 5 mm, considering particles smaller than 1 μm as nanoplastics (NPs). MPs have gained notoriety due to their toxicity and their role as carriers of other pollutants (Allen et al. 2019). They are known to adsorb various pollutants, both organic and inorganic, on their surfaces, effectively becoming a medium for transporting these pollutants to new environments where they were not originally present, causing further harm (Rios et al. 2007; Scudo et al. 2017). Unfortunately, due to the complex nature of MPs, the full extent of their impact on the environment is not yet fully understood.

MPs find their way into terrestrial and aquatic ecosystems through direct means, such as in paints, medical applications, electronics, coatings, adhesives, and as by-products of processes like thermal cutting and 3D printing. They can also enter these ecosystems indirectly through the breakdown and transportation of larger plastic debris (Brennholt et al. 2018; Koelmans et al. 2019; Ng et al. 2018). MPs and NPs are now recognized as emerging global pollutants of significant concern. Their small size makes them ingestible by various organisms, including humans indirectly. Furthermore, on a nanoscale, they can penetrate multiple biological barriers (Koelmans et al. 2019).

Despite the tremendous societal benefits that plastics have brought, enhancing practicality, convenience, and safety in daily life, improper disposal during production and after use, as well as the inefficiencies in wastewater treatment, have led to environmental pollution (De Sousa, 2021). Plastic pollution is a grave global issue, negatively impacting water resources, land, and the ambient air, with South Africa being no exception (Ubomba-Jaswa and Kalebaila 2020).

MPs find their way into natural environments, including freshwater bodies, the air, and land through various integrated pathways (Nikiema et al. 2022). These pathways encompass stormwater runoff, industrial effluent discharges, spillages, agricultural runoff, flood events, wastewater treatment plant effluent discharges, wind dispersion, atmospheric deposition, the application of wastewater sludge on agricultural soil, and inappropriate disposal of plastic waste on land (Alimi et al. 2021; Bank, 2022; Bouwman et al. 2018; Carr et al. 2016; Park and Park 2021; Mutshekwa et al. 2023; Ziajahromi et al. 2016). Azeem et al. (2021), in their comprehensive review, presented an estimation of plastic sources and transport pathways in the environment.

Extensive research is needed to thoroughly investigate the sources and pathways of MPs in the South African environment, as there is a lack of comprehensive reports on this subject. South Africa, like many other countries globally, faces complex challenges related to water pollution. Of particular concern is the emergence of environmental pollutants, with a shortage of scientific data to support and guide the regulation of MP pollution. The transformation of plastic waste into MPs poses a significant threat to the South African environment. While plastic pollution in marine environments is well-documented, there is a pressing need to understand the extent of pollution in freshwater sources and treated wastewater. The impact of MPs on inland areas, including potential effects on local ecosystems and biological processes in freshwater environments, remains largely unknown.

This review primarily focuses on assessing the levels and potential consequences of MPs in various contexts, including drinking water (both tap and bottled water), freshwater bodies and sediments (such as dams, rivers, and lakes), marine environments and their sediments (oceans), groundwater, rainwater, soil, fauna, flora, and humans. The aim is to make recommendations regarding affected areas, identify knowledge gaps, and outline the future direction for MPs research in the South African environment.

This study was conducted by reviewing literatures on MPs in South Africa's aquatic and terrestrial environments using multiple scientific databases over the past 30 years dating back from the first article on MPs in South Africa to the most recent article in 2024. The search included well-known platforms like Google Scholar, Science Direct, and Scopus. Although nearly 100 publications were found using "MPs in South Africa" as a keyword, the review narrowed down to only relevant articles that suits the aim of this review. Policy documents from South Africa and government reports were used to report on the estimation of plastic usage in the country.

Global trends and South African perspective on plastic production, disposal and degradation

Global plastic production has seen a steady increase over the years (Fig. 1), increasing from 1.5 million metric tons in 1950 to 367 million metric tons in 2020 (Plastics Europe 2021). This number is expected to increase to about 590 million metric tons in 2050 due to the

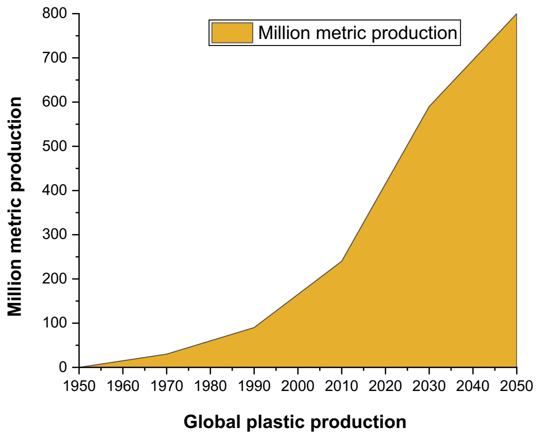

Fig. 1 Global plastic production has seen a steady increase over the years

adaptability and versatility of this group of materials (Statista 2023). In a review of global production, use, and fate of all plastics ever made, approximately 6300 Mt of plastic was generated in 2015, 9% of which was recycled, 12% was incinerated, and 79% was accumulated in landfills (Geyer et al. 2017). Geyer et al. (2017) predicted that if current production and waste management trends continue, an estimated 12 000 Mt of plastic waste will be disposed in landfills or the natural environment by 2050. Lebreton et al. (2017) modelled that, of 6300 Mt of plastic waste generated globally in 2015, between 1.5 and 2.5 Mt of plastics was transported by rivers into the ocean with the balance retained in the terrestrial environment. Ritchie and Roser (2018) categorized types of waste plastic material discharged to the ocean such as polypropylene (PP), low- and high-density polyethylene (PE).

South African plastic production is coal-based and contributes less than 0.5% of global plastic production (Department of Trade and Industry 2020). The coal is refined and polymerised into PE and PP virgin polymer powders. The virgin polymer powders are then granulated with either additives and/or fillers to maximise the beneficial properties of the virgin material depending on the application of the final product. The virgin material is sold to converters who in turn manufacture products for the packaging, building, agricultural, mining, automotive sectors, and other sectors of the economy.

In 2021, the plastic industry converted 1.2 Mt of polymer materials into plastic products. The production directly contributed 1.9% to the Gross Domestic Product (GDP), which translated to 15% in the manufacturing sector GDP (Plastics South Africa 2022). The plastic packaging sector contributed 50% of plastic products produced with 45% of the consumer market being dominated by PE low-density (PE-LD/LLD) and PP, followed by 28% of polyethylene high-density and polyethylene terephthalate (PET) polymer products (Plastics South Africa 2022). Despite the positive contribution of plastic products to the economy , inappropriate disposal practices post-use cause plastic waste pollution of the environment. The per capita consumption in South Africa is said to be about 30–50 kg per person leading to about 2371 million tonnes of plastic waste generated annually, a large percentage of this being single-use plastics, with a huge percentage ending up in the oceans and rivers and wastewater systems as a result of a poor waste management system (Sadan and de Kock 2020).

South Africa ranks 11th among the countries with the worst plastic waste pollutants (Jordan 2021). In 2019, plastic pollution cost South Africa about 885 billion rands in clean-up and recorded impacts on economic sectors like fishing with potential human risks (Bega 2021).

The flow of plastic materials in the plastic economy is predominantly linear, with 50% of durable plastic products designed for single use. These products often end up in landfills or are disposed of through open dumping, ultimately leaking into the environment (World Wildlife Fund, 2020). Plastics South Africa (2022) reported that in 2021, 1247 Kilo Tons per Annum (kt/a) of plastic waste was generated with 713 kt/a disposed at landfills and 43% recycled into the plastic economy cycle. In addition, The Council for Scientific and Industrial Research (CSIR), (2022), reported that, in 2020, 1546 kt/a of plastic waste was generated with 1350 kt/a disposed and processed at most inefficient local municipality landfills and 196 kt/a disposed on surrounding communal open grounds. The 19% of the total plastic waste generated was recycled back into the economy and 488 kt/a leaking directly into the environment due to poor management of plastic waste. The report found that 56% of plastic waste in the environment pollutes the air as it is openly burned, with 30% left to degrade on open ground communal land whilst 14% pollutes the aquatic environment. According to the World Bank Report on Plastic Waste Management (2021), which examines global rates of plastic waste generation, 368 Mt of plastic garbage were produced globally in 2020, with developing countries having difficulties with disposal and waste management (Stoett et al. 2024). The UN Environment Programme (UNEP) Report (2021) examines the situation of plastic pollution, emphasizing that more than 300 Mt of plastic are generated each year, with a substantial amount ending up in landfills, the environment, or the ocean, highlighting inefficiencies in waste management systems.

From intestinal obstructions to the transportation or leaching of toxicants employed in their manufacture or absorbed from the surrounding environment, microplastics can have toxicological effects on a variety of biota. Despite a notable growth, research on microplastics in Africa is still less advanced than in developed countries. In South Africa, 46 publications about microplastics have been published (Dahms and Greenfield 2024). Nevertheless, a lot of these papers employ techniques that may not be precise to provide comprehensive descriptions of microplastics in the environment.

Projection of environmental plastic waste pollution in South Africa

The CSIR (2022) modelled the plastic waste generation and pollution projection from 2021 to 2040 assuming a 1.33% Constant Annual Growth Rate (CAGR) based on 2020 plastic waste data. According to the results, plastic waste generation will double from 1546 kt/a to 2700 kt/a if linear management practices are maintained (Lebreton and Andrady 2019). A similar trend was observed with plastic waste pollution from burning of waste doubling up from 2020 quantities to 880 kt/a in 2040 (Ayeleru et al. 2020). The land and aquatic pollution moderately increased to about 350 kt/a and 100 kt/a in 2040, respectively. Interventions that optimize the combination of strategies of reducing demand, increasing collection, recycling and increasing safe disposal to landfill as well as reducing virgin input polymer materials demand scenario can avoid 63% total plastic pollution over the period 2023–2040, as compared to without any policies and intervention practices (Hira et al. 2022). In South Africa, the problems posed by these group of pollutants is especially severe as large number of the population are poor and live in regions where there is inadequate waste management infrastructure. These as well as a lack of public awareness, poor regulations and regulatory enforcements are some of the challenges of microplastic pollution.

Plastic waste degradation

The plastic waste accumulated in the environment as well as the recalcitrant polymeric materials with additives and fillers added during manufacturing undergo physical, chemical and biological degradation causing persistent MP pollution (Arutchelvi et al. 2008; United Nations Environment Programme 2016). The degradation process is unique to each environmental condition and type of accumulated plastic waste material (Lambert and Wagner, 2018; Sadan and de Kock 2020). The prolonged exposure of plastic waste materials to a host of environmental factors such as mechanical (compression, tension and/or shear forces), light (UV-light), thermal (temperature) and chemical (oxidative, hydrolysis) further degrades polymer material into MPs and nanoplastics (NPs) (O'Brien and Thondhlana 2019).

Source, transport and fate MPs in the South African environment

In South Africa, informal dumping, wastewater discharge, and plastic waste are the main sources of microplastics (MPs) pollution. They accumulate in sediments, biota, and water sources after being carried through freshwater systems, marine environments, soils, and air pathways. Environmental factors and polymer kinds affect the fate of MPs, which have an impact on ecosystems and human health.

Microplastics (MPs) in drinking water of South Africa

The presence of MPs in the freshwater environment used for drinking purposes is an emerging concern that needs much attention. In the South African environment, few studies quantified the levels of MPs in drinking water. Bouwman et al. (2018) reported that MPs were detected in drinking water in samples collected from the city of Tshwane and the city of Johannesburg in Gauteng province. The total MP levels of 0.189 particle L^{-1} and microfibre counts of 1.8 particle L^{-1} were reported. Ubomba-Jaswa and Kalebaila (2020) also highlighted that there are higher levels of finer MPs ranging from 20 to 300 μm than the large MPs in the treated water. Compared to other countries, MP levels ranging between 0.00015 and 12.6 particles L^{-1} have been reported from studies conducted on raw water sources in Europe, China, and the USA. Ubomba-Jaswa and Kalebaila (2020) indicated that 83% of drinking water samples analysed globally were found to contain MPs and fibres ranging from 0 to 57 particles L^{-1}. The lack of standard protocols for MP detection and quantification in drinking water makes it difficult to compare outcomes across different studies.

Microplastics (MPs) in South African freshwater and sediments

The study conducted by Bouwman et al. (2018) in the South African environment shows that freshwater contains MPs ranging from 0.33 to 56 particles L^{-1}. The highest total particles (fragments and fibre counts) were recorded in the Crocodile River that drains from most parts of Johannesburg. Ramaremisa et al. (2022) extracted MPs from surface water and sediment from the Vaal River in Johannesburg and the average abundances recorded was 160 ± 570 particles L^{-1} in the river water while in sediments, they recorded $4.6 \times 10^2 \pm 2.8 \times 10^2$ particles kg^{-1} dry weight . More than 80% of MPs reported in both water and sediments were fragments and fibres smaller than 2 mm. The dominant polymer types identified were PE-HD, low-density PE and PP in both water and sediments. Apetogbor et al. (2023) investigated the occurrence of MPs in water and sediments in the Plankenburg River, Western Cape, South Africa. Seasonal variation was conducted over four seasons to investigate their behaviour in spring, summer, autumn and winter. The spring water samples were found to contain the highest MPs of 5.13 ± 6.62 particles L^{-1} and the least, in autumn of 1.52 ± 2.54 particles L^{-1}. The average levels of MPs in sediment in springwas 1587.50 ± 599.32 particle kg^{-1}. The potential sources of these MPswere from surface runoff from urban centres, as well as from wastewater effluent discharged from households and industrial areas (Dalu et al. 2021). Higher levels of MPs have also been reported in developed countries including Europe, the United States and China (Bouwman et al. 2018). This gives a clear indication that plastic pollution is a global challenge that needs urgent intervention .

Studies have shown that freshwater fish near wastewater treatment plants ingest more microplastics during the wet season, with particles per fish species ranging from 10 to 119, compared to the dry season, where the range is 11 to 34 (Dahms and Greenfield, 2024; Dalu et al., 2024). This suggests that microplastic ingestion and resuspension are more prevalent during the rainy season. In the Plankenberg River the spring season had an average of 5,136.62 microplastic particles/L, compared to 1,522.54 particles/L in Autumn (Apetogbor et al. 2023).

Weideman et al. (2019) studied the effects of dams in reducing microplastic levels and transport into the marine environment and concluded that there is limited evidence to state that the construction of dams reduces the levels of MPs transportation to ocean. In 2020, Weideman and her coworkers reported that a little long-distance transport of microplastics in the Orange-Vaal River system, with a higher concentration in the upper parts than downstream (Weideman et al. 2020). The study found a mean of 2.3 ± 7.2 microfibres/L in the rainy season and 1.4 ± 2.6 microfibres/L in the dry season (Weideman et al. 2020).

Microplastics (MPs) in wastewater (domestic and industrial)

Microplastics are released into wastewater treatment systems basically via two major anthropogenic routes as well as several non-point sources. The collection of wastewater from homes contribute MPs to wastewater systems primarily through activities such as washing clothing and textiles and using personal care products. On the other hand, the discharge of industrial wastewater and effluents also contributes to the discharge of MPs to the environment. (Mason et al. 2016). Wastewater treatment plants (WWTP) are ideally designed to remove 40% to 90% of MPs per litre from wastewater (Magnusson and Norén, 2014; Talvitie et al. 2015). However, Periyasamy (2021) and Bailey et al. (2022) have also noted in their research that the majority of microfibres released during the washing process cannot be removed by WWTPs. The same view was also shared by Bashir et al. (2021), who also concluded that WWTP processes are not able to eliminate microbeads found in wastewater. The study conducted by Vilakati et al. (2021) in a Gauteng wastewater treatment plant in South Africa identified 23 pyrolyzate products in wastewater effluent resulting from polymer types such as PVC, polyamide (PA), PET and PE with contributions at 47.8%, 13.1%, 17.4% and 4.3%, respectively with 17.4% being attributed to additives from MPs.

The inefficiencies of local wastewater treatment systems coupled with consensus acceptance of the presence of MPs in wastewater do suggest that local freshwater systems are flooded with MPs. Vilakati et al. (2021) demonstrate that WWTPs are a major source of MPs in aquatic systems. The findings agreed with a previous study on MPs in some South African beaches, which discovered relatively higher quantities of MPs (i.e., microfibers) in sediments near wastewater treatment plant discharge points (De Villiers 2018). Furthermore, Dalu et al. (2021) in their study which was conducted in Vhembe district in Limpopo Province of South Africa investigated how urbanisation, and specifically wastewater treatment facilities, affected the distribution, kind, and prevalence of MPs along a subtropical river system. The study discovered that the MP type found in the study area were dominated by both microfibres and microbeads across all sites, but in some cases were lower downstream, suggesting that the wastewater treatment plant was playing some role in reducing MPs levels.

Microplastics (MPs) in South African marine water and sediments

Coastal sediments are a sink for MPs and this results in plastics remaining in the marine environment for exceptionally long periods. Depending on the chemical nature of each polymer, MPs are easily sorbed into the marine sediments. Studies conducted in South Africa showed the levels of MPs in marine sediments (Table 1). Vetrimurugan et al. (2020) reported higher levels of MPs contamination in the South African beach sediments from the southeastern coast of South Africa. The type of polymers identified include PP, polyester (PES), and PET in sediments. Other MPs such as nylon (NY), polycarbonate (PC), polyacrylonitrile (PAN) and rayon (RY) were also found in the sediments. The levels of MPs recorded were higher than in most beaches globally and this is a sign for urgent intervention by implementing constant monitoring and evaluation of MPs.

Table 1 Concentration of MPs in marine sediments in South Africa

Location	Concentration (MPs Kg^{-1})	References
Port of Durban	2400–45,867	(Preston-Whyte et al. 2021)
Durban Beaches	5466.6–16,866.6	(Vetrimurugan et al. 2020)
Braamfontein	4–1347.5	(Dahms et al. 2020)
South coastline	0–567	(De Villiers 2018)
Grahamstown Bloukrans	83	(Nel and Froneman 2018)
Coastline 2700 km SA	84	(Sparks and Immelman 2020))
Durban Bay	100–1900	(Matsuguma et al. 2017)
Southeast Coastline	678	(Ryan 1990)

Several studies have reported on MP levels in marine water across South Africa (Table 2). Higher levels were recorded in marine sediments in comparison to freshwater (Table 2). The common source of MPs in marine water includes wastewater discharge, surface runoff and discharge from other surface water bodies.

Microplastics (MPs) in groundwater of South Africa

Groundwater is a source of drinking water for most people in the world, this is particularly true in developing countries where over half of the population depends on groundwater for drinking and domestic purposes (Mutoti et al. 2023; Edokpayi et al. 2022). Although MPs has been largely reported in riverine and coastal regions of the world its level in groundwater is sparsely reported (Viaroli et al. 2022).

In South Africa, very few studies have evaluated MPs levels in groundwater even though most of the population depends on groundwater for consumption. Bouwman et al. (2018) reported low levels of fragments and fibres in boreholes (n = 4) waters from Potchefstroom, Northwest Province. The levels of MPs were in the range of 0.12–0.29 particles L^{-1} with a mean level of 0.17 particles L^{-1}. The composition of the MPs was largely PES, PP and polystyrene (PS). The possible mechanism for groundwater contamination was not reported as well as the potential health risk associated with the levels found. Higher levels of groundwater contamination from MP have been reported in Nigeria. Oni and Sanni (2022) reported the levels of MPs (206 to 1691 particles L^{-1}) in groundwater samples from Lagos, Nigeria. Higher levels were recorded in groundwater from highly industrialized regions of the city compared to less industrialised regions. There is sparse literature on the levels of MPs in groundwater from developing countries, including South Africa, and more studies are recommended as a large portion of the population depends on it.

There is however a likelihood of groundwater contamination from MPs due to the horizontal and vertical transportation from agricultural soils during mulching and landfill sites. Owing to the importance of groundwater as a source of drinking water it is paramount to evaluate the occurrence of MPs in them to protect the health of the consumers. Groundwater contamination with MPs can occur during surface and groundwater interactions, and infiltration of water-carrying MPs in contaminated sites such as solid waste deposition places like landfills. Artificial recharge of groundwater with stormwater or effluents of WWTPs are all potential routes of groundwater contamination of MPs (Mutoti et al. 2023). The infiltration of landfill leachate mostly in unlined landfills presents a possible route of contamination. In addition, the geology

Table 2 Concentration of MPs in marine water in South Africa

Location	Concentration particles L^{-1}	References
Port of Durban	41.50–143.5	(Preston-Whyte et al. 2021)
Richard Bay (Durban)	413.3 ± 77.73	(Nel and Froneman 2018)
South East Coastline	257.9–1215	(Nel and Froneman 2015)
Braamfontein	705	(Dahms et al. 2020)
Ocean (Durban)	40.1	(Naidoo and Glassom 2019)
South-East coastline	1.215×10^6	(Nel and Froneman 2015)
Estuaries (Durban)	1.49×10^{-7}	(Naidoo et al. 2015)
South Western (Cape Town)	3.64×10^6 MPs m^{12}	(Ryan 1988)

of soils can facilitate groundwater contamination. Several studies from Europe and America have reported various levels of water-carrying MPs into groundwater (Ganesan et al. 2019; Panno et al. 2019).

Microplastics (MPs) in South African soil environment

The land-based sources of MPs and the pathways that lead to freshwater and marine pollution have been studied (Verster and Bouwman 2020). The common problem was that most of the formal solid waste and wastewater management facilities are not fully operational, and this has contributed to more release of plastics into the environment (Verster and Bouwman 2020). The latest story on a local newspaper, Daily Maverick (https://www.dailymaverick.co.za/article/2023-04-11-earthcrimes-free-state-municipalities-foul-failure-on-wastewater-treatment/) highlighted that Free State municipalities' wastewater treatment is non-functional, and this is not only in the Free State but is common at many municipalities in South Africa. Due to the failure to implement a proper plan of environmental management, a large quantity of plastics enters the environment directly via informal and illegal dumping. Once plastics degrade in the environment they form MPs and are transported and distributed by air to soil with complex dynamics to understand the source point (Prata 2018). There is scarcity of data on MPs in South African soils as most studies are focused on water, sediment, and biota. De Souza Machado et al. (2019) reported the need to look at the size and type of MPs as well as environmental factors including illegal dumping and wind actions that lead to plastics deposition on soil. The most elaborate data set available currently covers aspects of plastic on coastal (beaches) compared to inland (Verster and Bouwman 2020). The disposition of nappies on beaches that were observed in informal settlements needs more attention even in the inland soils (Plastics South Africa 2022). This is a clear indication that there is a lack of sufficient data and knowledge gaps concerning the occurrence and distribution of MPs in the soil in the South African environment and that require urgent attention through research and monitoring. This would assist in minimizing plastic entering the natural environment by taking actions on illegal and informal dumping.

Aquatic biota (fauna) of the marine environment in South Africa

Varying levels of MPs have been reported in marine aquatic fauna (Table 3). Fish, larvae, shrimps, and crabs have been recorded to ingest MPs. Such ingestion could be due to the MPs mimicking as food and are easily ingested by the fauna thus making a possible pathway for ingestion by other organisms higher in the food chain and then to man. Several techniques have been reported for the analysis of MP in marine biota in South Africa. The visual examination method has been reported to characterize MPs found in *Chelon richardsonii* sampled from the Sunday Beach surf zone (Algoa Bay) in South Africa, using a modified fine-mesh seine net with 500 µm mesh. Fibres and fragment MPs were the most common MPs detected in most fish studied. It is also crucial to note that the visual identification of MPs, particularly fibres, is susceptible to inaccuracy since natural fibres may be mistaken for MPs (McGregor and Strydom 2020).

Attenuated Total Reflectance Fourier Transform Infrared (ATR-FTIR) method was also used to explore the various forms of MPs in young fish muscles and the study revealed that fibres and fragments were the most common morphologies while RY, PES, PA, and PVC were the most common plastic kinds (Naidoo et al. 2020). Bakir et al. (2020) reported that 67% of the MPs consumed by three fish species from the ocean in Cape Town were made of fibres. Other studies using different biota along the South African coastline also reported similar results (De Villiers 2019; Naidoo et al. 2016). The primary polymers found in the fish guts were identified using

Table 3 Concentration of MPs in some fish and larvae in the marine aquatic environment in South Africa

Location	Sample	Concentration	References
Cape Town	Mytilus galloprovincialis	3.4 MPs $Fish^{-1}$	(Sparks et al. 2021)
	Choromytilus meridionalis	5.6 MPs $Fish^{-1}$	(Sparks et al. 2021)
	Aulacomya ater	2.9 MPs $Fish^{-1}$	(Sparks et al. 2021)
Agulhas Bank	Fish Species	3.72 MPs $Fish^{-1}$	(Sparks & Immelman 2020)
Mangroves (KZN)	Juvenile Fish	0.9 MPs $Fish^{-1}$	(Naidoo et al. 2020)
Braamfontein	Chironomus spp. larvae	53.5 MPs Kg^{-1}	(Dahms et al. 2020)
Grahamstown Bloukrans	Chironomus spp. larvae	7.4×10^{-7} MPs Kg^{-1}	(H. Nel & Froneman 2018)
Southeast coastline	Polychaete	2.75×10^{-4} MPs Kg^{-1}	(Sparks & Immelman 2020)
Durban harbour (KZN)	Mugil Cephalus	3.8 MPs $Fish^{-1}$	(Naidoo et al. 2016)

ATR-FTIR, and they were PE, PA, PET, and PP. On the other hand, PET and low-density polyethylene (LDPE) were discovered utilising the potassium bromide (KBr) technique for FTIR analysis of sediment samples, with PET present in the majority of them (Mehlhorn et al. 2021). The Plankenberg River was the first in the Western Cape to be studied for microplastics, demonstrating seasonal variations. The spring had an average of 5.13 ± 6.62 microplastic particles/L, compared to 1.52 ± 2.54 particles/L in Autumn (Apetogbor et al. 2023).

The extent to which microplastic (MP) pollution is threatening existing aquatic resources is yet unknown, although it is growing globally and has a variety of effects on aquatic wildlife. Since coastal communities rely significantly on marine resources for nutritional protein and waste treatment may not be at its best in developing nations, MP-induced hazards to marine fauna are particularly serious. The significance of MP contamination for African fishing resources was evaluated. Several studies have documented the effects of microplastic pollution on South African species. Dahms and Greenfield (2024) reported on the presence of microplastics in the gut of Cape River Crabs which were found to reduce their feeding efficiency. Microplastics were also found in the digestive tracts of African Penguins, Southern Right Whales and in the tissues of marine mussels which could affect their growth and reproductive capacities (Dahms and Greenfield 2024; Pereao et al. 2020).

In South Africa, a network of pertinent phrases revealed a focus on plastic products, freshwater environmental contamination, and fish health issues in Mediterranean waters. Compared to other regions, the MP contents of fishing resources from the Gulf of Guinea and the Nile countries, followed by Tunisia, are substantially higher. Since some of the most polluted species are also some of the most exploited, MP pollution poses a threat to lucrative but already vulnerable African fishing resources. There were significant geographic gaps with virtually little information on MP in aquatic animals, particularly in freshwater and along the coasts of East Africa. The significance of improving plastic waste management on the continent and expanding the coverage of MP pollution in African fishing resources is highlighted by these findings.

Microplastics (MPs) in humans in South Africa

Plastic debris are transported into the environment from different sources, while only 19% of plastic waste is recycled and a large percentage of plastic debris continues to pollute the environment (Stafford et al. 2022). The degradation of plastics influenced by environmental factors including photodegrading poses a short and long-term health problem if there is mismanagement of plastic waste. Naidoo et al. (2020) described how dumping of plastics may result in negative health effects on humans. There are knowledge gaps in examining the health effects of MPs distributed in the South African context. Plastic waste has been acknowledged globally as a serious health concern by various studies in other developed countries (Stafford et al. 2022). The effect of MPs on health is also of public concern in South Africa. More work on plastic waste chemical components introduced during plastic production is required to avoid plastic products that directly interact with liquids and food.

The study conducted by Naidoo et al. (2020) recorded the ingestion of plastic in marine species including sharks (n = 10), fish (n = 7), turtles (n = 1) and birds (n = 36). The consumption of shellfish may, therefore, be a possible pathway for the introduction of MPs into humans (Naidoo et al. 2020). The scientific data on levels of transfer of MPs from different sources (mussels, oysters etc.) to humans is still limited. There is no reported scientific data in South Africa on the high dietary seafood content in terms of investigating population level. This includes pathways of MPs through drinking water and airborne (inhalation) to humans*.*

Characterisation of microplastics (MPs) in the South African environment

The characterisation of MPs and their fate in different environmental media is reported in terms of size, density/concentration, functional polymer group and morphological properties (Aragaw, 2021). The various techniques for characterisation of MP in the environment are used to qualify and quantity them.

Methods used for analysis, advantages and disadvantages

MPs research in South Africa is sparse, with most of the studies evaluated determined the composition of MPs in water, sediments, and biota using either visual examination, stereo microscopy, Raman microscopy, scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA) and gas chromatography (GC). Visual examination by the naked eye and/or stereo microscopy provides a rapid analysis which provides an overall idea of the MPs present, in terms of size, shape, and colour (Rodrıguez-Seijo and Pereira 2017). However, the visual techniques are prone to inaccuracies, resulting in fibre misidentification (Alimi et al. 2021).

Analytical instruments such as Raman microscopy, SEM, FTIR, TGA and GC analysis offer additional benefits compared to visual inspection which includes size and morphology characterization as well as accurate polymer type identification and quantification. Raman spectroscopy can identify particle size in the range of

1–20 µm, however, it is subjected to fluorescence interferences due to ineffective separation and purification techniques (Aragaw, 2021). The SEM provides highly reliable morphological properties of nano-sized particles but cannot identify the functional group of polymers (Aragaw, 2021). FTIR is used to identify the functional groups, especially of particle sizes greater than 20 µm, TGA is independent of particle size but ineffective with polymer types that have well-defined melting points. GC is effective in providing the molecular mass of polymers greater than 500 µm (Aragaw, 2021).

Fourier Transform Infrared Spectroscopy (FTIR) and Scanning Electron Microscopy (SEM) are important tools for analyzing microplastics, but each has limitations. Visual microscopy is often employed before the use of FTIR. This can lead to exclusion, bias and misidentification. Identifying microplastics in complex samples is challenging due to FTIR's inability to detect smaller particles (less than 20 µm) and possible contamination from adjacent contaminants (Azari et al. 2023). Furthermore, FTIR is not the most effective approach for quantifying microplastics in heterogeneous materials (Rathore et al. 2023). Also, FTIR involves careful and sometimes rigorous sample preparation which can lead to the exclusion of some particles (Willans et al. 2023). The use of FTIR in microplastic identification is as good as the spectral library incorporated with it. An incomplete library can lead to misidentification or exclusion (Kozloski et al. 2024). Unless combined with other technologies, such as Energy Dispersive X-ray Spectroscopy (EDX), SEM produces exact images of particle shape but lacks the ability to identify chemical compounds (Girão et al. 2017). Even when combined with EDX, Sem still struggles to detect elements like carbon and oxygen which are important in the determination of plastic types (Girão et al. 2017). It also has trouble recognizing microscopic microplastics and may lose samples during preparation. SEM is also more expensive and less suitable for complicated investigation (Girão et al. 2020). Both procedures require competent operators for proper interpretation and are vulnerable to sample contamination (Azari et al. 2023). To improve microplastic analysis accuracy, FTIR and SEM can be combined with techniques like as Raman spectroscopy and robust sample collecting (Z. Huang et al. 2023).

Types of microplastics (MPs) characterized in the South African environment

Despite being categorised in terms of sources, MPs are further classified in terms of type of MPs based on shape (fibres, microbeads, nurdles fragments, and styrofoams) and colour (Rodrıguez-Seijo and Pereira, 2017). The fibres are generally associated with textile fleece clothing from the washing process, microbeads from cosmetic products such exfoliators, kinds of toothpaste and body scrubs, nurdles used as pellets for plastic products manufacturing and fragments as well styrofoams from the degradation of plastic waste materials (Hamed et al. 2021).

The fibres are found to be irregular to spherical and long-thin fibres with plastic pellets having tablet-like, oblong, cylindrical, spherical, and disk shapes, with rounded ends (Hidalgo-Ruz, 2012). The fragments and styrofoam are described as rounded/and or angular with microbeads as granules (Wagner et al. 2014). The colour of MP is also used in the characterisation of MP, albeit not conclusive as it is mainly influenced by the source of production and rate of degradation in the environmental compartment. Transparent/white colours are typically associated with single-use packaging plastic materials, with deep rich colours such as black, blue, red, yellow, and other colours being linked with resistant packaging material and other plastic goods (Aragaw, 2021).

The type of MPs found in the environment is dominated by transparent/white MP fibres, which concentrate in sediment during dry spells with WWTPs' effluent and/or communal domestic usage of rivers being reported as potential sources. These fibres were also found in aquatic organisms and were reported to be found at the mouth of the Vaal-Orange River, along the riverbanks of lower reaches of catchments along the south and east coastline, the shoreline of Nandoni Reservoir and Braamfontein Spruit by Weideman et al. (2020), Villiers (2019), Mbedzi et al. (2020) and Dahms et al. (2020), respectively. Dahms et al. (2020) described the fibres/filaments found in Braamfontein spruit as having round and angular shapes with transparent/white being the dominating colour. Mbedzi et al. (2020) did not describe them in terms of shape but found the dominant colour being white with PS being a dominant polymer type followed by PE and PP. Dahms et al. (2020) and Nel et al. (2018) found black and blue MPs respectively ingested by *Chironomus spp* larvae which could be linked to the slow degradation of resistant packaging material (Aragaw, 2021). The increase in concentration/density of MPs was found to be influenced by population density, anthropogenic activities such as WWTPs effluent discharge and communal domestic usage of rivers.

Fate and impact of microplastics (MPs) on the South African environment

Microplastics (MPs) in soil

MPs are emerging environmental pollutants that pose a threat to the environment, and this may have a potential risk to agroecosystems in terms of food safety (Barboza et al. 2018). The majority of studies investigated the colour, shape, particle size, and identification of various polymers in soil (Auta et al. 2017; Du and Wang 2021). To have a deeper understanding of environmental behaviour and the impacts of MPs, it is critical to look at the composition and morphological characteristics of MPs (Beaumont et al. 2019; Sparks et al. 2021). This may give clarity on the distribution, migration, transformation, fate, and ecotoxicological effects of MPs in the terrestrial system.

The physical properties of soil may be changed by MPs introduced into the soil matrix (Guzzetti et al. 2018; Bakir et al. 2020). The interaction between MPs and various soil properties as well as other environmental factors drives the migration and retention of MPs in the soil (Alimi et al. 2021; Zhou et al. 2020). The migration behaviour and key process of MPs in the terrestrial environment remain to be determined. Therefore, MPs in soil pose a threat to microbial-plant-animal function and health as they may enter the human body via the food chain (Dris et al. 2017; Grause et al. 2022).

MPs may affect the physicochemical properties of soil, and this includes the effect of the soil biota such as earthworms and changes in soil aggregation, bulk density, and water-holding capacity (Cao et al. 2017). The effects of PP fibres, PE fragments, PET fibres, and PA microbeads on bulk density, water-holding capacity, and water stability in soil aggregates vary among different MPs (Guo et al. 2020). MPs can carry different bacteria, fungi, algae, and other microbes that may result in detrimental effects on the soil's physical environment (Naik et al. 2019; Fu et al. (2020). Plastic mulching widely used in agroecosystems (crop fields) may cause soil degradation (Liu et al. 2018; Corradini et al. 2019). Nutrients in the soil and carbon stocks may be reduced by mulching and the plastic debris residues may release chemical additives (Liu et al. 2018; De Souza Machado et al. 2019). Additives to plastic including Bisphenol A may leach into the soil and can form toxic endocrine-disrupting substances after accumulating in the soil system (Sharma and Chatterjee 2017; Barboza et al. 2020). The depletion of soil organic matter may also be influenced by MPs deposition with the sorption of trace metals (Lang et al. 2020); (Liu et al. 2020); (Joo et al. 2021). A large quantity of MPs is also deposited in sewage sludge from WWTPs and the biosolids recovered after drying sludge are being used as supplements of nutrients in the soil thus providing a major pathway of MPs into the terrestrial environment (Petersen & Hubbart 2021). De Souza Machado et al. (2018) reported the effects of PP fibres, PET fibres and PE fragments on bulk density, water stability aggregates and water holding capacity, and their effects may differ. For instance, in soil contaminated with PET fibers, water stability aggregates and bulk density decreased with increasing PET concentration while in PP and PE effects were not similar.

MPs may remain in the soil after the nutrients are absorbed by plants and distributed along with the soil system via bio-physicochemical processes (Lang et al. 2020; Liu et al. 2020). The topsoil horizon acts as a degradative platform for physical and chemical changes of plastic debris due to photodegrading (ultraviolet radiation), intense temperature, and high oxygen content (Wu et al. 2020). The physical change in plastic debris via biodegradation occurs with the assistance of soil microbes and terrestrial biota (Wan et al. 2019). The degradation of plastics in soil takes place slowly and this can be for decades (Kukkola et al. 2021). Therefore, the high persistence of MPs in soil has potential toxicity risks to the soil system (Guo et al. 2020). Leaching of chemical additives via the degradative process can result in MP pollutants entering groundwater.

Plastics dumped in landfills could be distributed in the environment by wind and mishandled waste by rubbish collectors may lead to MP pollution. After dumping plastics in landfills, chemical additives may leach from dumped plastics, and it is influenced by physical, chemical and biological processes (Qi et al. 2020). For instance, plasticizers, colourants, reinforcements and stabilizers may be leached based on the polymer type. The fluctuation in the physical properties of soil may be due to variations in MPs dose exposure based on the soil mineralogy, distribution of pore size, and humus (Liu et al. 2020). The soil's physical properties related to MPs affect plant growth including photosynthetic efficiency and root growth, this may also have effects on the uptake of nutrients by plants from the soil (Wang et al. 2020). MPs may also fluctuate the water percolating capacity and soil water holding capacity, and this can affect evaporation (Wu et al. 2020). Therefore, MPs may change the soil–water cycle, incline soil water shortages, and affect the migration of environmental pollutants among cracks in soil horizons (De Souza Machado et al. 2019; Machado et al. 2019). Therefore, more work needs to be done to have a good understanding of the harmful effects of MPs on the physical properties of soil.

The impacts of MPs in various soil types may affect the chemical properties of soil in terms of their transfer and soil nutrient cycle (Duis and Coors 2016; Boots et al. 2019). This may be the effects on soil enzymes with high catalytic properties, especially in diacetic acid luciferin and others (Cao et al. 2021). Ding et al. (2020) indicated that high levels of PP polymers in soil improve the carbon content, nitrogen, and phosphorous nutrients dissolved in organic matter. This may be due to MPs promoting the soil enzyme activity and its accumulation of soluble nutrients. Soil properties, such as hydrogen ion activity, electrical conductivity, as well as carbon–nitrogen ratio may assist in the evaluation of the effects of various

MPs on the soil. To have a deeper understanding of MPs' behaviour in the terrestrial system, it will also be critical to have a laboratory setup, as well as established field experiments. The balance of the two may assist in terms of adequate replication and appropriate controls on the long-term solutions to MPs' impacts (Wang et al. 2020). The applied knowledge in field setup may bring an understanding concerning the negative effects of plastic debris on MPs influenced by soil hydrogen ion activity, cation exchange, porosity, texture, aggregates, and other environmental factors. Several studies confirmed that plastic residues affect the properties of soil, and this mostly results in unsustainable agroecosystems for use (De Souza Machado et al. 2019; Ding et al. 2020; Wang et al. 2020). Most research on the occurrence and impacts of MPs has largely focused on the aquatic ecosystem and mostly on coastal regions and less work has been reported inland, and this has limited the quantification of MPs in soil and their pollution potential (Ratnasari et al. 2024). The determination of the MPs threshold may assist in the evaluation of the spatial scale of MPs pollution, transport rate and the prediction of loading capacity received in agroecosystems (Gao et al. 2019).

Microplastics (MPs) in plants

MPs are widely distributed and may interact with various aquatic species including duckweed, vetiver grass, crops, etc. There is more to be done to find clarity on how MPs adsorb and accumulate via phytostabilisation to plant surfaces (Harms et al. 2021). Plants may trap MPs in nearby water systems through various mechanisms including biofilm, the morphology of plant surface, and electrostatic interactions based on polymer characteristics (Hartmann et al. 2017). MPs absorbed by plants may be transferred through the food chain to herbivores and carnivores including humans (Wang et al. 2018; Helcoski et al. 2020). In South Africa, there is limited data on the impacts of MPs on aquatic higher plants. According to Huang et al. (2021), MPs have inconsiderable impacts on higher plants as well. The chlorophyll content in duckweed *Lemna minor* and its growth rate may not be affected by PE MPs with sizes ranging from 4 to 45 µm and this reduces the cell viability and growth of plant roots (Khalid et al. 2020). MPs may effectively penetrate the cell wall surface and pose a potential risk to various plant species (Bellas and Gil 2020). PS MPs may also accumulate in the spore surface of aquatic plant species like fern *Ceratopteris pteridoides* and be absorbed into the roots. This shows that MP pollution needs much attention as it poses a threat to both aquatic and terrestrial systems as it enters environmental media in different pathways (Bhattacharya and Khare 2020). MPs polymer exposure may negatively affect the growth and reproduction of some aquatic plants in their life cycle and pose a threat to other species like ferns (Bhattacharya and Khare 2020; Li et al. 2021). The toxicity of MPs on phytoplankton especially microalgae was investigated (Li et al. 2021; Maity et al. 2022) and the findings showed that MPs are accumulated in phytoplankton via penetration through the cell wall. Further research on the potential effect of MPs on higher aquatic plants need to be considered.

Microplastics (MPs) in the river ecosystem

MPs enter the aquatic environment from different sources and pathways that contribute to MPs pollution in the river ecosystem (Weideman et al. 2019). This includes microbeads from personal care products, microfibres from synthetic textiles, rubber fragments from tyre abrasion, and runoff from landfills and agriculture (De Villiers 2018; Dahms et al. 2020).

MPs reside in and float on several parts of the river water system depending on their density when disposed of within the aquatic environment (Dai et al. 2018). This might be due to the low density of MPs compared to that of river water (Pereao et al. 2020). The characteristics of MPs that influence their behaviour include surface properties, partial crystallinity, oxidation resistance and biodegradability (Guilhermino et al. 2018). The distinct chemical composition of river systems may have contrasting effects on the fate and transport of MPs (Egessa et al. 2020). Therefore, in a condition where saline water mixes with river water from different tributaries the impact of this mixture and wave turbulence may influence the MPs density, size and charge (Hernandez et al. 2017; Guilhermino et al. 2018). This may cause a loosely clumped mass of fine MPs particles and result in much higher MP deposition within the river ecosystem (Horton and Barnes 2020). MPs transportation may also depend on the hydrological attributes of the river systems including the physical properties of the river water like topography, water depth, and water flow velocity in different seasons (Jambeck et al. 2018). The high-water flow can result in the displacement of sink MPs and afterwards discharge the MPs to the surrounding river ecosystem (Kataoka et al. 2019). The low water flow conditions may lead to an increased accumulation of MPs in the river ecosystem (Kowalski et al. 2016). In South Africa, most of the part of the country receives more rain during summer (rainy season) than in winter (dry season) and the transportation of MPs in river systems significantly depends on the rainy season and this affects the river flow rates as well as the fate and transport of MPs. According to Bhan et al. (2024) the percentage of MPs reported in rivers are discharged into the marine environment.

Microplastics (MPs) in sediments

MPs can sink and accumulate in the sediments when their ability to float loses momentum in low water flow (De Villiers 2019). In some previous studies, multiple investigations pointed out that MPs sediment pollution is a global challenge due to its widespread, particularly in coastal shallow water zones and this shows that more needs to be done in the inland shallow water zones (Matsuguma et al. 2017; Mehlhorn et al. 2021). MP concentrations in sediments may be similar to those in river water as they can arise in high water flow from sediment settlements (Kowalski et al. 2016; Nel and Froneman 2018). Naidoo et al. (2015) reported that MPs level in sediments averaged between 745.4 ± 129.7 particle kg^{-1} in urban estuaries of KwaZulu Natal province in South Africa. Sediments accumulate most of the MPs transported from different sources including densely populated areas like townships and municipal wastewater discharge sites (Weideman et al. 2019).

The distribution of MPs in sediment differs between the rainy season and the dry season (Verster and Bouwman 2020). The MP abundances in samples collected during the rainy season were less compared to the dry season and this might be due MPs carried by high river flow during heavy rains (Verster and Bouwman 2020). In South Africa, MPs pollution in sediments has been documented more along the coast compared to inland river ecosystems (Sparks and Immelman 2020; De Souza Machado et al. 2018; Sparks and Immelman 2020). Based on studies conducted for beach sediments, there is a high possibility that MP particles accumulating in beach sediments are from inland river ecosystems especially from domestic and sewage effluents. Kosore et al. (2018) indicated that 149 MP particles were recorded in coastal Kenya with a range of 33.3–275 MP particles and the major findings of this study pointed out that there is an escalation in the abundance of MPs in an offshore direction. It is critical to note that the majority of the MPs that end up accumulating in the sediments are from anthropogenic activities including illegal dumping on unauthorised sites (Alimi et al. 2021).

Therefore, terrestrial habitats including sediments on the river floor are considered large MP reservoirs, which may pose multiple exposure pathways to the aquatic biota in the river ecosystem and this may also change the environmental geochemical conditions and result in environmental toxicity (Vilakati et al. 2021). Accumulated MPs in the sediments may interact with other potentially harmful inorganic and organic pollutants, and their high levels in sediments make them more bioavailable to various terrestrial biota (Alimi et al. 2021). Due to MP's high surface area and hydrophobicity, they may act as carriers of pathogens and organic pollutants on sediments (Auta et al. 2017). Microorganisms attached to MPs pose a threat to the ecosystem by conveying MPs from the sediments to aquatic biota and, eventually, to other living organism through the food chain (Chico-Ortiz et al. 2020).

Microplastics (MPs) in aquatic biota

The physical and chemical properties of MPs may have a detrimental effect on organisms such as shrimps, zooplankton, crabs, omnivorous and carnivorous (Naidoo et al. 2020). MP particles can have a direct chemical impact on aquatic systems through ingestion by aquatic biota and this is due to the potential pathways of MPs for trophic-level migration in the aquatic environment (Pereao et al. 2020). After ingestion, MP particles may cause damage to the digestive system through internal blockage (Bakir et al. 2020). MPs as well as smaller particles aggregate in their digestive tract and may enter and accumulate in the circulatory system (Sparks and Immelman 2020). MPs particle size influences its accumulation in various organisms, which may have an impact on living organisms' reproduction and growth (Sparks and Immelman 2020).

The smaller MPs particle size may be easily absorbed and accumulated by aquatic species, and this may reduce the growth rate, longevity and fecundity of aquatic species (Bosker et al. 2019; Rondoni et al. 2021). Other findings pointed out that MPs can penetrate intestinal epithelium into biological tissue, and this may cause serious harm to aquatic species (Duis and Coors 2016; Helmberger et al. 2020). MPs interact with different pollutants and may transport toxic chemicals, through the intake of MPs, to the aquatic species and the pollutants adsorbed on the MPs may be bioavailable (Alimba and Faggio 2019; Hüffer et al. 2019). They can also be released during plastics degradation to the aquatic system (Hurley et al. 2018). The carried toxic chemicals may be absorbed by other polymers including polychlorinated biphenyls (PCBs) which have carcinogenic, teratogenic and mutagenic effects on aquatic species (Hüffer et al. 2019; Akdogan and Guven 2019). The pollutant's bioavailability affects molecular and cellular pathways (Alimba & Faggio 2019).

Health impact and the fate of microplastics (MPs) in animals and humans

MPs in environmental media may lead to exposure to both animals and humans (Novotna et al. 2019). There is limited scientific data on the effects on animals and human health based on current MP concentrations. This is because more studies are conducted along the coastline than inland (Nel and Froneman 2015; Sparks et al. 2021).

MPs may change the soil permeability and interfere with the biogeochemical processes which may lead to

Table 4 Summary of records of South African vertebrates found to be entangled or to have ingested plastic (Naidoo et al. 2020)

	Entanglement organisms		Ingestion	
	Number of species	Main plastic type	Number of species	Main plastic type
Sharks	8	Plastic bands/straps	10	Plastic bags and sheets
Bony fish	Not distinguished from an active gear		7	Fragments and fibres
Turtles	2	Rope	1	Fragments, films and pellets
Birds	265	Plastic bags and line	36	Fragments, pellets and foams
Mammals	5	Nets, rope, line, straps	0	–

human health impacts (Zang et al. 2020). MPs exposure routes in humans may be through ingestion, inhalation, and direct dermal contact (Yu et al. 2020). Ingestion is mostly the primary route of MPs. MPs may be consumed via the drinking of water from water bottles as well as the consumption of kinds of seafood like bivalves (mussels), fish and shrimps (Wang et al. 2020). MPs in animals and humans can cross the gastrointestinal epithelium and enter the human body in the size range of 100–150 µm (Athey et al. 2020). Some studies indicated that MPs particle size of 10 µm may enter the cellular membranes and organs by passing through the placenta and blood–brain barrier (Carbery et al. 2018; Bulannga and Schmidt 2022). A recent study shows the detection of MPs in the breastmilk of a woman, hence providing another possible pathway to children (Li et al. 2021). The impacts of MPs on human health are limited and should be further explored to protect the health of the public.

Microplastics' harmful effects were studied in a variety of experimental settings, including cells, organoids, and animals (Zhu et al. 2023). The consequences include oxidative stress, DNA damage, organ failure, metabolic imbalance, immune response, neurotoxicity, and reproductive and developmental injury (Zhao et al. 2024). Furthermore, epidemiological studies indicate that microplastic exposure may be linked to a few chronic illnesses (Lee et al. 2023). The breathing of air contaminated with MPs from the atmosphere forms another possible pathway of human exposure to MPs. MPs can constitute part of particulate matter (PM 2.5 and PM10) and this can have negative effects on the respiratory system (lungs in particular) (Astner et al. 2019; Bradney et al. 2019).

MPs inhaled per person annually might be from various sources including clothing, landfills, building materials as well as abrasions from plastic products (Vilakati et al. 2021). Therefore, it would also be critical to look at MPs in local dust both in an informal settlement and urban areas as inhalation of MPs may be more occurrent than via the ingestion pathway. Comparative studies showing various pathways of human exposure as well as estimating the potential impact remain knowledge gap that needs to be fully explored globally and in developing settings like South Africa. Due to poor handling of waste in many municipalities in South Africa, there is much illegal dumping which results in more unwanted items being carried away to the aquatic and terrestrial systems. With the accumulation of MPs in human lungs with very thin tissue (1 µm), MPs can form a matrix with blood and transport it via blood into the entire human body (Iroegbu et al. 2020). The last MP exposure route can be through direct dermal contact with local dust as well as personal care products (Iroegbu et al. 2020). MPs can enter the skin through washing or scrubbing with cosmetic and personal care products, particularly particles smaller than 100 nm (Luo et al. 2020).

Due to various MPs' exposure routes stated above, MPs pose a threat to human health (Table 4). MPs are reported to have effects on human health and the challenge is that these effects need to be studied in detail as they are poorly understood. Examples of active chemical compounds included in some additives and fillers are summarized in Table 5 (Bank, 2022; Bolgar et al. 2015; Bouwman et al. 2018; Hahladakis et al. 2018; Wagner and Lambert, 2018).

They can be accumulated for a long time in the environment media and the human body (Table 5). The

Table 5 Examples of additives and fillers with respective active chemical compounds

Description	Active chemical compound
Plasticisers	Bis(2-Ethylhexyl) terephthalate
Accelerants	Ethylene thiourea
Crosslinks	2-Mercaptobenzothiazole
Flame retardants	tetradecachloro-p-terphenyl
Antidegradents	N,N′-bis(1,4-Dimethylpentyl)-p-phenylenediamine
Antioxidants	2–2-Hydroxy-5-tert-octyl phenyl benzotriazole
UV stabilizers	2-(2-Hydroxy-5-methyl phenyl) benzotriazole
Antizonants	Nickel dibutyl dithiocarbamate
Biocides	Arsenicals, organotin, triclosan and mercury
Photosensitizers	Benzophenones
Surfactants	Polysiloxanes
Pigments	titanium oxide
Fillers	Calcium carbonate, clay, talc and carbon black

extended duration of MPs exposure can cause oxidative stress and cytotoxicity, alteration of metabolism balance, translocation of MPs to distant tissue, disruption of immune function, and as well as a vector of environmental contaminants such as toxic chemicals (Barboza et al. 2018).

During manufacturing, metallic ions and persistent organic pollutants (POPs) can be adhered to MPs and act as carriers releasing those environmental contaminants into the environment (Tang et al. 2021). MPs in the environment are dominated by microorganisms to form biofilms (microorganisms including pathogens stick on MPs to form biofilms) which alters the MPs' characteristics and may influence their potential risks (Sun et al. 2019). MPs change physically and chemically and their change in properties means different behaviour in the environment (Table 6). Biofilms on MPs change the properties of MPs including the hydrophobicity, roughness, density, particle size, and functional group of polymers (Pereao et al. 2020). The study of Steinmetz et al. (2020) pointed out that the toxic effect of MPs may differ in terms of functional groups in each polymer.

Mitigation methods

MPs are persistent in the environment and are not easily degradable and as a result need to be removed from the environment. Removal of MPs can be classified into two broad forms; prophylactic and treatment solutions (Wong et al. 2020).

Prophylactic measures

These involve measures taken to ensure MPs do not enter the ecosystem. These include the imposition of bans on plastic littering/dumping and in some cases, the bans may be on the use of plastic products themselves like the use of MPs in cosmetic products (Wong et al. 2020). Preventive measures also involve encouraging manufacturers to use bioplastics, especially in packaging and other single-use applications (Peelman et al. 2013). Another prophylactic measure that can be employed is the enforcement of recycling. Plastic manufacturing companies can be made to collect and recycle their plastics with fines imposed for noncompliance.

Treatment solutions

Separation and degradation are the two major methods that have been employed in the remediation of MPs (Picó and Barceló, 2019). These can be broken down into physical, chemical and bioremediation methods. Some of the most common methods employed include electrocoagulation (Perren et al. 2018); (Horton and Barnes 2020), sediment-MP isolation (Coppock et al. 2017), cellulose nitrate filter membrane (Magni et al. 2019), fluidisation and flotation (Nuelle et al. 2014), nanoparticle (Ya et al. 2021) sol–gel method (Nguyen et al. 2021), membrane technology (Li et al. 2018), advanced filtration technologies (Lares et al. 2018) and other chemical methods like the use of iron and aluminium salt coagulants and ultrafiltration (Lares et al. 2018). Biological methods like the use of microorganisms (Harrison et al. 2011) and adsorption using Fucus vesiculosus (the edible marine microalgae seaweed) (Sundbæk et al. 2018) have also been employed. The interaction between MPs and plants has not been investigated thoroughly. A few studies by Bhattacharya and Khare, (2020) and (Davarpanah and Guilhermino 2015) had conflicting results when looking at the impact of MP uptake by different plants.

Physical method of microplastics (MPs) remediation

Methods like filtration, sedimentation, and adsorption have been employed in the removal of MPs in water. Adsorption is arguably, the most efficient physical method of remediation of MPs. Adsorbents like magnetic polyoxometalate-supported ionic liquid phase (magPOM-SILP) composite (Misra et al. 2020), magnetic carbon nanotubes (Tang et al. 2021) have been successfully employed in the removal of different types of MPs (initial concentration of 5 *g*/L) with 100% removal efficiency. (Yuan et al. 2020) applied three-dimensional reduced graphene oxide in the adsorption of PS and obtained

Table 6 Summary of Microplastic Findings Across Environmental Sectors

Environmental sector	Location/region	Microplastic concentrations	Dominant types	Source(s)	References
Water	Gauteng River System	10–50 particles/L	Polyethylene (PE), Polypropylene (PP)	Industrial effluents, urban runoff	(Vilakati et al. 2021)
	Coastal Waters (e.g., Durban)	5–30 particles/L	Polystyrene (PS), Nylon	Maritime activities, urban waste	(Naidoo and Glassom 2019)
Soil	Agricultural Lands	500–1000 particles/kg	PE, Polyvinyl chloride (PVC)	Plastic mulching, fertilizers	(Mutshekwa et al. 2023)
Biota	Marine Organisms (e.g., fish)	2–10 particles/organism	Microfibers, PE	Ingestion from water, prey items	(Masiá et al. 2022)

a removal percentage of 56, 53, and 66 with tap water, MP-polluted water, and distilled water respectively. Zinc metal–organic framework-based wood aerogel composite material was used by (You et al. 2022) to remove poly (1,1-difluoroethylene) and PS with removal percentages of 92 and 88 respectively, in seawater.

Another physical method that has been employed in MP remediation is filtration which is said to be representative of other methods like flotation and sedimentation (Park and Park 2021). Filtration encompasses such methods as sand filtration, disk filtration, and all membrane filtration methods like ultrafiltration, nanofiltration, dynamic membrane and reverse osmosis (Park and Park 2021). Disc filters, and zirconium metal–organic framework-based foam materials have been used as filters with removal percentages of 90 and 96 respectively (Chen et al. 2020). Talvitie et al. (2017) compared the removal efficiency of MPs using disc filtration and rapid sand filtration in WWTPs and found them to remove 98.5% and 97%, respectively. MPs in pre-treated landfill leachates were removed by Zhang et al. (2021) employing a combination of ultrafiltration, nanofiltration, and reverse osmosis with a removal percentage of 75. (Wang et al. 2020) used corn straw biochar and hardwood biochar in combination with silica sand to filter MPs in a wastewater treatment plant and had a 95% removal rate.

They compared this with filtration using silica sand alone where the removal percentage was 60–80%. One disadvantage of this study is that they only used uniformly graded MP spheres. Rapid sand filtration was compared with membrane bioreactor in the removal of 14 different types of MPs in a wastewater treatment plant's final effluent and removal efficiencies of 75 and 79%, respectively were obtained (Bayo et al. 2020). Shen et al. (2020) have also described the work done by Ziajahromi et al. (2016) on the removal of MPs from wastewater using membrane separation (ultrafiltration, nanofiltration and reverse osmosis) methods with a significant reduction in MP load.

Chemical methods of microplastics (MPs) remediation

The chemical method of MP remediation usually involves the removal of MPs through chemical reactions like precipitation, redox reactions like ozone oxidation, photocatalytic oxidation and catalytic oxidation, gas floatation, electrolytic methods and others (Gan et al. 2021). These methods can be destructive and non-destructive.

Coagulation and flocculation

Coagulation, a chemical method of MP removal, is usually used with sedimentation and filtration. It involves the introduction of a positively charged coagulant to neutralize the negative charges on suspended and dissolved MP particles to form insoluble particles (Krystynik et al. 2021). This process is usually followed by gentle agitation called flocculation to aid agglomeration. These large aggregates are then separated by sedimentation and filtration (Zhao et al. 2021).

Esfandiari and Mowla (2021) investigated the removal of MPs from greywater (household wastewater) using coagulation and dissolved air flotation. They employed aluminium and iron-based coagulants in the removal of PS and achieved 96% and 70% removal respectively. Aluminium chloride and iron (III) chloride have been employed as coagulants combined with ultrafiltration in the removal of PE (Ma et al. 2019). Their results were in line with what (Esfandiari and Mowla 2021) obtained but their removal percentage was lower at 37%. This value was improved up to 91% by the addition of anionic polyacrylamide. The effect of ionic surfactants on the coagulation of MPs was studied by Skaf et al. (2020) and Xia et al. (2020). They both found that anionic surfactants improved the coagulation of MPs while non-ionic surfactants had the opposite effect.

Degradation

Degradation is a series of steps or processes that leads to the decline in properties such as crystallinity, and mechanical and thermal stability of polymeric materials (Singh and Sharma 2008). Degradation could be photochemical, photocatalytic, mechanical-chemical, ozone, catalytic or biological (Krystynik et al. 2021). In aquatic environments, degradation can be enhanced by sand and waves and by air and sunlight for particles on the water's surface (Song et al. 2021). Biological activity also plays a role in the degradation of MPs but this effect is rather negligible in deep oceans (Song et al. 2021).

Photochemical degradation, which is material degradation (breakdown of molecular bonds and production of radicals) with the aid of UV light has been used by many researchers and is one of the most preferred methods in polymer degradation. For example (Tribedi and Dey 2017) reported that the microbial degradation of LDPE in the soil is aided by peroxidation, in a study where they compared the degradation of LDPE in soil with and without UV treatment. Their findings revealed that UV treatment increases the double-bond index of LDPE, making it more prone to microbial degradation. This study was, in essence, a combination of photochemical and microbial degradation. (Zhu et al. 2020) also studied the degradation of PE, PP and PS in seawater with the aid of simulated sunlight. Visible surface changes, as well as increased dissolved organic carbon, were used as indicators of MP degradation.

Photocatalytic degradation, which is similar to photochemical degradation except for the addition of a photocatalyst, has been used by several researchers to remove MPs in water. For example, (Piazza et al. 2022) applied the photo-fenton process using ZnO nanorods, surface grafted with SnOx(x < 2) and zero-valent iron (FeO) nanoparticles as catalysts in MP degradation, monitoring the process with an FTIR. It was discovered that lower molecular weight compounds (carbonyl and vinyl groups) were formed which implies successful degradation. Nabi et al. (2020) studied the photocatalytic degradation of PS and PE over titanium oxide nanoparticle films under UV rays. They reported 98.4% mineralization in 12 h for polystyrene but did not report the percentage degradation for polyethylene. Protein-based porous N-TiO_2 semiconductor was used as a photocatalyst in the degradation of HDPE with promising results (Ariza-Tarazona et al. 2020). Ariza-Tarazona et al. (2020) and Vital-Grappin et al. (2021) also performed a similar study using C, and N-TiO_2 as photocatalysts. They discovered that optimal conditions of low pH and low temperature aided MP degradation. Despite the positive results reported by these and other researchers, Xu and Ni (2022) reported that photocatalytic degradation on its own is not sufficient for complete MP removal. They instead, employed a combination of photocatalytic degradation (using a ZnO-based photocatalyst) and coagulation.

Phytoremediation of microplastics (MPs)

Phytoremediation is a process where the natural functions of plants are used to remediate contaminated soil, sediment, surface, and groundwater (Das 2018). Liu et al. (2019) showed the possibility of MP accumulation in plants but as highlighted by Ebere et al. (2019), very little research has been done on MP uptake by plants. Austen et al. (2022) carried out one of the few comprehensive studies on the uptake of MPs by woody plants. They introduced MP beads (PA powder), tagged with fluorescent dyes, into the soil (the concentration of MP in the soil was 0.043%) before planting birch trees. Root samples were then examined in the 5th month using fluorescence and confocal laser scanning microscopy. They were able to locate and visualize MP particles in root hairs, the outer epidermal layer, vascular tissue of lateral root, as well as root exodermis and cortex. One drawback of this study was the size of MP particles used (5–10 µm). In another study, Rozman et al., (2022) investigated the uptake of MPs by the floating macrophyte, *Lemna minor*. They discovered that, although root length of the plants was initially affected by the presence of MPs, specific growth rate, total antioxidant capacity, contents of energy-rich molecules, electron transport activity and chlorophyll content were not affected. They concluded that the plants could uptake MPs from water with high bio-adhesion and withstand high concentrations of MPs for long periods. Table 7 compares the major methods described above and looks at the advantages and disadvantages of each method.

Policies, legislation and strategies to mitigate the increase of microplastics in the South African Environment

There is no formal specific legislation/policy to regulate plastic production except plastic waste in South Africa. Plastic production was initially managed through a best practice voluntary scheme until recently in May 2021 when mandatory Extended Producer Responsibility (EPR) Regulations were promulgated in terms of the National Environmental Management Waste Act of 2008 was enacted to assist and promote the plastic packaging industry to move from traditional linear production to the preeminent circular economy (WWF, 2020). Plastic waste generation is managed through the (NEM: WA, 2008) as overarching legislation for all sectors of the

Table 7 Microplastic remediation techniques applicable in South Africa

Technique	Description	Application	Advantages	Limitations
Mechanical filtration	Use of fine meshes to capture microplastics	Wastewater treatment plants	Cost-effective, scalable	Limited efficiency for nano-sized plastics
Electrocoagulation	Removes microplastics via electrochemical methods	Industrial effluent treatment	High removal efficiency for diverse sizes	High energy consumption
Biodegradation	Employs microorganisms to degrade plastics	Soil and water remediation	Eco-friendly, targets specific plastic types	Long degradation periods
Phytoremediation (vetiver grass)	Plants trap and remove microplastics in soil	Agricultural fields, wetlands	Cost-effective, enhances biodiversity	Limited to non-toxic microplastics
Advanced oxidation processes	Chemical breakdown of plastics into harmless byproducts	Polluted waters	Effective for persistent microplastics	Requires advanced technology and high cost

economy that generate waste. It is only in the recent 2020 National Waste Management Strategy that plastic waste has found explicit expression in the regulatory framework. However, in May 2003 in recognition of plastic waste as a threat environment, Plastic Carrier Bags and Plastic Flat Bag Regulations were promulgated (Nhamo 2003). The regulations were targeted at the reduction of plastic bag waste generation and disposal, which was initially successful (there was an 80% reduction) but after the reduction of the levies due to poor participation from some stakeholders, plastic bag consumption continued to rise (O'Brien and Thondhlana 2019). The back-and-forth discussion of all role players in the waste sector came to a consensus and gave effect to the EPR regulations (EPR Regulations, 2021) which eventually held the plastic and packaging sector liable for the fate of the wastes from their products, starting from production to consumption and consequently generation of MPs (Olatayo et al. 2022).

Microplastic contamination is becoming a bigger problem, especially in surface waterways where microplastics are common, such the Vaal River. According to studies, there are typically 0.68 particles per cubic meter, with fibres and fragments being the most prevalent types (Saad et al. 2024). Urban areas and industrial operations, such wastewater treatment plants, are important contributors of pollution (Singh et al. 2023) because they can spread and be consumed by organisms, the distribution is dominated by smaller particles (< 0.5 mm), which is problematic for environmental health (Ziani et al. 2023).

The results regarding the prevalence and destiny of microplastics (MP) in South Africa highlight the pressing need for legislative measures to reduce plastic pollution and its negative effects on the environment and human health (Okeke et al. 2022). Increased MP levels in sediments, soils, and water bodies, along with ineffective wastewater treatment, underscore the need for better WWTP technology and more stringent laws governing single-use plastics. Promoting environmentally friendly plastic substitutes, standardizing MP detection techniques and improving waste management infrastructure are examples of solutions. Effective environmental regulations and the implementation of focused remediation solutions depend on public awareness campaigns and strong partnerships between industry, researchers, and legislators (Table 8).

Conclusion and recommendations for future research

This review investigates the prevalence and fate of microplastics (MPs) in South Africa's freshwater, marine, and terrestrial environments, highlighting major findings and knowledge gaps and suggesting future research areas. Drinking water samples from Tshwane and Johannesburg contained finer MPs (20–300 µm), which were more frequent. However, the lack of standardized regulations makes comparison with worldwide statistics difficult. MPs were found in different quantities in freshwater bodies and sediments, with higher amounts in the Crocodile and Vaal Rivers, which were dominated by polyethylene (PE-HD), low-density polyethylene, and polypropylene (PP). Seasonal fluctuations in MP levels were detected, with a peak in the spring.

Wastewater treatment plants (WWTPs) were found as a major source of microplastic contamination in aquatic habitats, with severe inefficiencies in MP removal. Higher levels of MPs were identified in sediments near the southeastern shore, which contained polymers such as PP, PES, and PET. Marine biota, including fish, were discovered to consume MPs. There is limited data on MP concentrations in South African groundwater, but further research is needed given the country's reliance on groundwater as a drinking water supply. Soil contamination from informal and illegal dumping was also identified as a

Table 8 Policy Framework Addressing Microplastics in South Africa

Policy/legislation	Objective	Relevant sector	Key provisions	Implementation challenges
National environmental management act (NEMA)	Sustainable management of natural resources	Environmental protection	Provides guidelines on waste management, including plastic pollution	Limited enforcement and monitoring capacity
Waste management act	Regulates waste generation and disposal	Waste and recycling	Mandates reduction, recycling, and recovery of plastic waste	Low public awareness, insufficient infrastructure
Coastal management act	Protects coastal and marine environments	Marine conservation	Addresses pollution sources, including microplastics in coastal areas	Weak integration of microplastics in current policies
Plastics Pact (South Africa)	Industry-led initiative to reduce plastic use	Manufacturing and trade	Targets 100% reusable or recyclable plastic packaging by 2025	Industry participation remains inconsistent

significant source of MPs, which can impair soil characteristics and plant growth.

The study acknowledges a scarcity of studies on MP uptake by plants, indicating a need for additional research in this field. It also highlights the scarcity of data on human exposure to MPs, with probable mechanisms including ingestion through drinking water, seafood, inhalation of airborne MPs, and skin contact.

Environmental variables such as wind action (airborne) and surface runoff must be investigated as sources of plastic pollution in soil, river sediments, and plants. Plastic pollution should be investigated from land-based sources to the marine environment. This is because South Africa is ranked as the 11th worst contributor to marine plastic pollution. According to forecasts, 15 000 to 40 000 tonnes of plastic are carried into the maritime environment each year. South Africa should establish a plan to reduce informal and illegal dumping to reduce the amount of plastic entering the freshwater and marine environments.

Although South Africa is a signatory to multilateral environment agreements on plastic waste pollution, the country is increasingly overburdened with inappropriately disposed plastic waste with unacceptable consequences (Pariatamby et al. 2019; Plastics South Africa 2022). Given the widespread production of plastic and application of plastic products, high volumes of generated plastic waste, inadequate waste management in South Africa and the possible input of MPs in the environment due to semi-degradation, MPs, can therefore, be classified as pollutants of emerging concern in the South African environment. To gain insights into the status of MPs and their impact on the environment as well as mitigating strategies and technologies, a review of the research conducted in South Africa in the past 10 years has become necessary. Similarly, limited research has been carried out on their impact on the terrestrial environment.

Finally, the study advocates for immediate action to address the major environmental and human health consequences of MP pollution in South Africa. It emphasizes the importance of multidisciplinary research to close knowledge gaps, as well as effective policymaking, public participation, and finance to manage plastic trash and promote sustainable alternatives. Various remediation strategies, including as physical, chemical, and biological procedures, were investigated, with an emphasis on their benefits and drawbacks. To address MP pollution, a holistic approach is required, including research, policy, and technology solutions.

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