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Stormwater outlets: A source of microplastics in coastal zones of Cape Town, South Africa

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ABSTRACT

The runoff from stormwater outlets are potential sources of microplastics (MPs) in coastal zones. The characteristics and concentrations of MPs in coastal water, sediment and biota (mussels, whelks and sea urchins) were measured in summer (2020/2021) (dry season) and winter (2021) (wet season) from three sites (Camps Bay, Mouille Point and Three Anchor Bay) in Cape Town. MPs were characterised visually using a stereo microscope and chemically using spectroscopy. MP concentrations were higher in water and sediment during winter, and higher in biota in summer. Compared to control sites, MPs were higher at all impact sites sampled. MPs extracted were mainly black polyester (PEST) fibres, 1000 to 2000 μm in length averaging 0.15 MPs/L in water, 52.11 MPs/kg dry weight in sediment and 1.35 MPs/g soft tissue wet weight in biota. The results indicate that coastal stormwater systems are potential sources of MPs in the coastal environment of Cape Town.

1. Introduction

The marine environment is constantly impacted by anthropogenic activities that bring a wide range of pollutants to coastal ecosystems. Plastic pollution has been a notable problem since the 1950s and, in the 21st century, has been a noticeable global problem in the water environment (Eerkes-Medrano et al., 2015; Vegter et al., 2014). Approximately 80 % of plastics introduced into the marine environment are from land-based sources via wind and water from large coastal cities (Jambeck et al., 2015). According to Jambeck et al. (2015) about 4.8–12.7 million tonnes of plastic waste are estimated to be released into coastal regions annually. The waste products that have attracted much attention in recent years are microplastics (MPs). MPs can be defined as plastic polymers smaller than 5 mm and can be found as either primary or secondary MPs (Mvovo, 2021). Primary MPs are raw plastic material used to produce plastic products (e.g. nurdles), while secondary MPs are formed from the breakdown of larger plastic products (Mvovo, 2021; van Wijnen et al., 2019). MPs are known to enter the marine environment through wastewater treatment system effluent, rivers and stormwater systems (Yin et al., 2021; Jannö, 2016; Jönsson, 2016; Weideman et al., 2020).

Due to the urbanisation of the coastal region and with the coastal populations on the rise, the coastal environment is affected by anthropogenic materials (Gartner et al., 2002). Poor waste management and waste management structures are increasing the degradation of coastal marine ecosystems (Francescangeli et al., 2020). Drainage structures such as stormwater outlets are poorly designed to remove anthropogenic materials such as MPs in runoff. The runoff, including MPs, contains high quantities of chemicals and contaminants that are commonly discharged into shallow coastal waters (Wanielista and Yousef, 1993; Cox and Foster, 2013).

According to Jannö (2016) and Jönsson (2016), rivers and stormwater outfalls, depending on the season, are key sources of introducing MPs into the coastal environment. These drainage structures are designed to transport large volumes of water from streets to prevent flooding (Weideman et al., 2020). Due to their poor design, stormwater systems in South Africa collect waste from terrestrial land via runoff and deposit it in the coastal region without being screened or treated (Weideman et al., 2020). It is estimated that South Africa releases 0.09–0.25 million tonnes of plastics from land-based sources to coastal areas, with Cape Town contributing 40 % of this (0.04–0.1 million tonnes) (Collins and Hermes, 2019). Coastal ecosystems in South Africa are impacted by stormwater outlets, with Weideman et al. (2020) estimating that as much as 570 t of plastic is released into Cape Town

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coastal waters from stormwater systems. MPs have been documented in South Africa coastal waters (Nel and Froneman, 2015), sediment (Preston-Whyte et al., 2021) and biota (Sparks, 2020). Due to MPs being ubiquitous in the coastal region, water, sediment and biota such as filter feeders (mussels), grazers (sea urchins) and carnivores (whelks) are susceptible to MPs as they can be found directly adjacent to stormwater outlets.

In the coastal zones of Cape Town, rocky shores are often found adjacent to stormwater outlets and are vulnerable to MP contamination. Non-selective and/or filter-feeders such as mussels and sea urchins are prone to being impacted by MPs (Moore et al., 2001). Since mussels are ubiquitous around South Africa's rocky shoreline, they are an ideal organism to monitor MPs (Sparks, 2020). MPs have been recorded in various other invertebrates like polychaetes, in which Nel and Froneman (2018) recorded 0.28 MPs/g dry weight. Many other invertebrates, especially on rocky shores, are vulnerable to MPs ingestion. Mussels (filter feeders), sea urchins (grazers) and whelks (carnivores) are organisms that can be found in both the intertidal and subtidal zones in rocky shores along the Cape Peninsula and were selected to indicate different feeding groups that may take up MPs. Given the lack of MPs research around stormwater outlets in South Africa, the aim of this study was to investigate the presence and characteristics of MPs at three impacted and non-impacted (control) stormwater outlets. The objectives set out by the study is to compare concentrations of MPs in water, sediment, and three different feeding groups between impact and control sites, to assess seasonal differences in the concentrations and polymer composition of MPs in water, sediment and three different feeding groups at stormwater outlets. During summer (dry season) and winter (wet season), MPs were extracted from water and sediment samples in the intertidal zone and coastal invertebrates (mussels, sea urchins and whelks) sampled from the intertidal and subtidal zones.

2. Methodology

2.1. Study area

The study area was the west coast of the Cape Peninsula, Cape Town, South Africa (Fig. 1). Cape Town falls within an eastern boundary coastline of the cool Atlantic Ocean, which is dominated by the Benguela Current (March et al., 2022). The area is known to be dominated by south-easterly winds during the summer dry season that creates upwelling, which is known to increase productivity, and predominantly northward winds prevail during the wet winter season (de Vos et al., 2021). The study comprised three locations, each area having an impact and control site (at least 150 m away from impact sites). The study areas that were selected are: Camps Bay (−33.9528 S, 18.3749 E), Mouille Point (−33.8991 S, 18.4092 E) and Three Anchor Bay (−33.9063 S, 18.3975 E). Each location was adjacent to residential/commercial areas and is accessible for recreational activities by the public. All locations were relatively sheltered sites, with the Three Anchor Bay control site being the most exposed to the open ocean.

2.2. Sampling

Samples consisted of abiotic components (water and sediment) and three different invertebrate feeding groups: filter feeders (mussels –

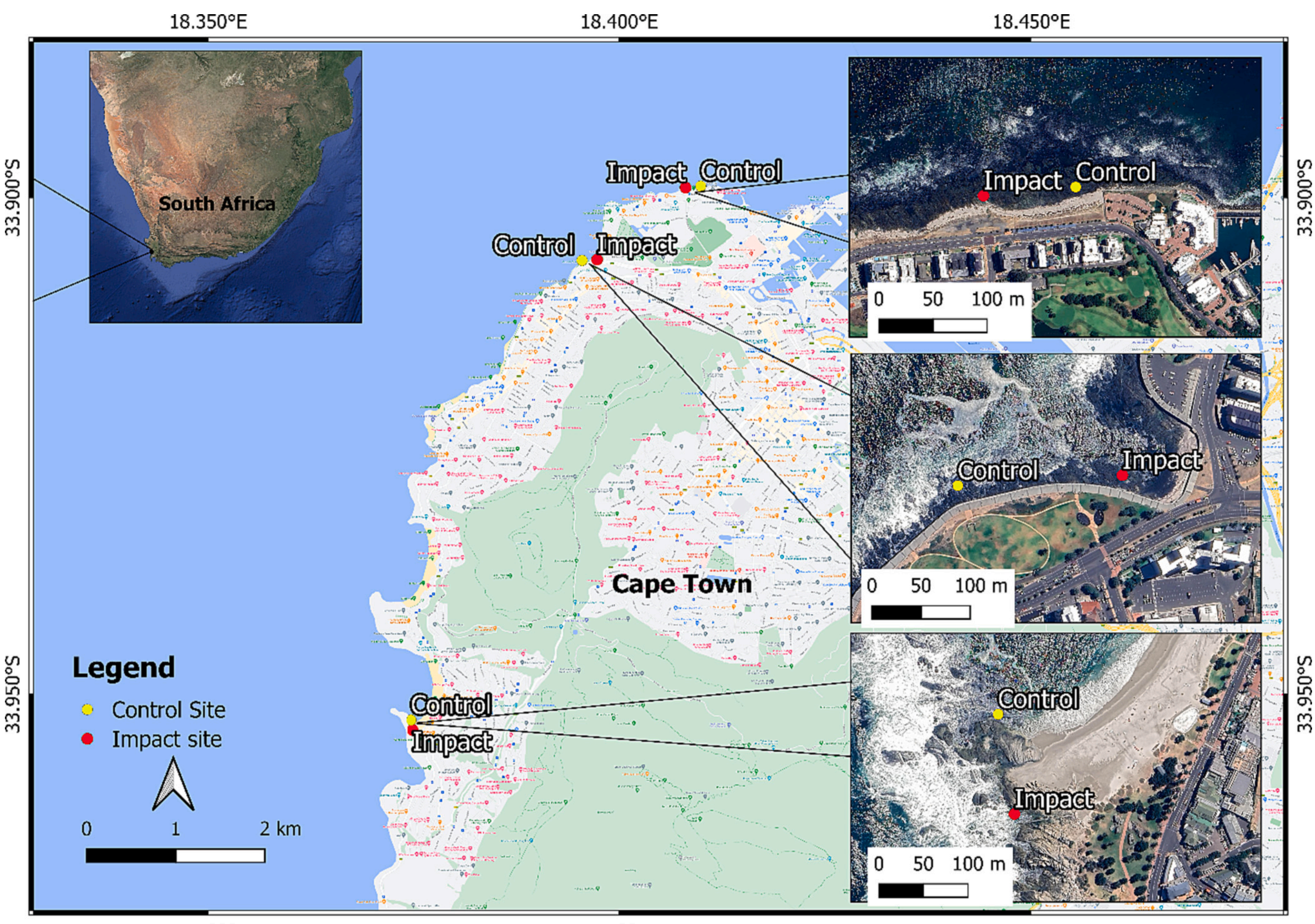

Fig. 1. The Cape Peninsula study area and study sites chosen to assess impacts of the selected intertidal stormwater outlets.

Mytilus galloprovincialis), grazers (sea urchins – *Parechinus angulosus*) and carnivores (whelks – *Burnurpena* sp.). At each impact and control site 20 individuals were collected (if available) per organism as well as five sediment and water samples. Two sampling periods took place during low tides, with a total of 1362 samples collected during summer (642 samples) (11–14 December 2020) and winter (720 samples) (21–27 May 2021).

For water samples, five replicates were collected using a metal bucket at the intertidal zone at a depth between 0 and 0.5 m and 100 L of surface water were taken per replicate and filtered through a 250 μm mesh (hence 500 L were processed per location). Particles remaining on the mesh was transferred to a pre-cleaned 50 mL falcon tube and stored at −20 °C until analysed. Water was collected downwind to prevent potential contamination of samples. Five replicate sediment samples were taken 5 m apart at the strandline. A metal spoon was used to collect the top 5 cm of sediment, within a 0.25 m × 0.25 m quadrat and stored in Ziploc bags. No sediment was collected at the control site for Three Anchor Bay as there was no sediment available at the site. At Impact and control sites 20 mussels, sea urchins and whelks, respectively, were collected in both the intertidal and subtidal zones. Subtidal samples were collected by snorkelling between 1 and 3 m depths, while intertidal samples were collected on rocky shores. Samples were inserted into pre-cleaned Ziploc bags and stored at −20 °C until analysed.

2.3. Microplastic extraction

Extraction of MPs from water, sediment and biota samples was done based on the methods of GESAMP (2019). Water samples in falcon tubes were left to defrost and added to glass jars that were rinsed with ultra-pure MilliQ water. For all stored samples, storage containers were rinsed at least three times. Each sample was then digested by adding 10 % KOH at a ratio of 1:2 and placed in an oven at 50 °C for 24 h, which is done to remove any biological matter that is likely to be mistaken as MPs. The digested sample was then added to a Buchner funnel and samples filtered using a vacuum pump. All samples were filtered onto a pre-cleaned 20 μm nylon mesh and inserted into pre-cleaned petri dishes to dry before being analysed. At least 300 g of sediment was removed from the Ziploc bags, placed into aluminium containers and placed in an oven for a minimum of 48 h at 50 °C or until constant weight. A 200 g replicate of each sample was digested in 10 % KOH with a ratio of 1:2 in an oven at 50 °C for 24 h. Samples were allowed to cool, then the supernatant from each sample filtered through a Buchner filtration system, fitted with a 20 μm nylon mesh. After which a hypersaline solution (NaCl 360 g/L) (pre-filtered through a 10 μm mesh) was added to the sediment residue (3:1) and mixed well for roughly 2 min before allowing it to settle for 15 min, then the resulting supernatant filtered through the Buchner filtration system. This process was repeated three times using the same filtered saline solution for each sample. The mesh was then carefully removed and inserted into a pre-clean petri dish before being analysed. For laboratory analysis of biota, all organisms were left to defrost and the soft tissue wet weight (stww) (in grams) measured for each organism. The soft tissue of each sample was added to a glass jar, 10 % KOH added and then allowed to digest at 50 °C for 24 h. The digested sample was filtered through a Buchner filtration system fitted with a 20 μm nylon mesh. The mesh was then carefully removed and inserted into a pre-clean petri dish before being analysed.

2.4. Visual identification

Putative MPs retained on the nylon mesh were identified using a stereo microscope (Zeiss Stemi DV4) at 40× magnification. MPs were identified based on their shape (fibres, fragments, spheres, filaments), colour (white, transparent, red, yellow, black, blue) and size (<100 μm, 100–500 μm, 500–1000 μm, 1000–2000 μm, 2000–5000 μm, >5000 μm) (GESAMP, 2019). The criteria for potential identification of MPs was based on: (1) particles did not have cellular or biological features, (2) fibres should have the same thickness along its entire length, (3) fragments were hard particles with smooth or angular edges and (4) particles should be uniform in colour (Hidalgo-Ruz et al., 2012).

2.5. Polymer identification

Fourier-transform infrared spectrometry (FTIR) was used in the determination of MP polymers. In total, 488 suspected MPs were analysed, using a PerkinElmer Two ATR-FTIR, following methods of Sparks et al. (2021). A background scan was done before analyses of MPs and the ATR crystal was cleaned before each sample, to prevent inaccurate identification. FTIR scans were obtained from spectral wavenumbers from 4000 to 450 cm^{-1}, intervals of data set at 1 cm^{-1}, resolution at 4 cm^{-1} and scans at 10 per sample. The minimum size limit of MPs that were analysed with the FTIR was set to 500 μm. Scanned particles were compared with polymers from the reference library (ST Japan) and matches above 60 % accepted. Examples of microplastics scans using FTIR can be seen in Fig. 2.

2.6. Quality control

Several steps were taken to minimise contamination in the field and laboratory. For sample collection, storage containers were pre-cleaned with ultrapure MilliQ water. When filtering water at the sampling sites, containers were held down-wind to avoid airborne contamination from clothing. Controls at each site were taken by placing an empty jar at the site location. To minimise contamination of microplastics in the laboratory, cotton white coats and sterile gloves were worn during all procedures and work areas cleaned with alcohol before starting procedures. All samples stored for digestion were covered with foil before being filtered. All equipment used to process the samples were washed three times with ultrapure MilliQ water. As a preventative measure, all windows and doors in the lab were closed during analysis. A damp filter paper was placed at a workstation while samples were being processed.

Controls that were taken during sampling and processing of samples are: site air control (no contamination recorded), lab air controls (the amount of MP contamination found in the lab air control were minimal and not included in MP data analyses) and Ziploc blanks (no contamination recorded). Hypersaline and digestion solutions were filtered through a 10 μm mesh to prevent contamination across samples.

Recovery success rate of MPs was done to identify the retrieval percentage of each method used from water, sediment, and biota for this study. Twenty neon purple-red MP fibres, sized between 1000 and 2000 μm were added to five replicate samples for water, sediment, and biota. The recovery rate of each tested method was as follows: water – 100 %, sediment – 85 %, biota – 100 %.

2.7. Data analysis

Concentrations of MPs in this study were reported as units/L for water, /kg dry weight (dw) for sediment and /g soft tissue wet weight (stww) and /individual (I) for invertebrates. The data recorded was evaluated using the Kolmogorov-Smirnov test for normality and the Levene's test for variance. Data were not normally distributed, even after log transformation. Non-parametric Mann Whitney (MW) tests were used to analyse MPs between two groups, Kruskal-Wallis tests across more than two groups and pairwise comparisons done between impact sites across locations. All analyses and graphs were done using SPSS v28. The variance of the data for statistical analysis was reported as standard error (SE) and significance of parameters set at $p < 0.05$. It should be noted that no sediment was collected at the control site for Three Anchor Bay as there was no sediment available at the sampled area.

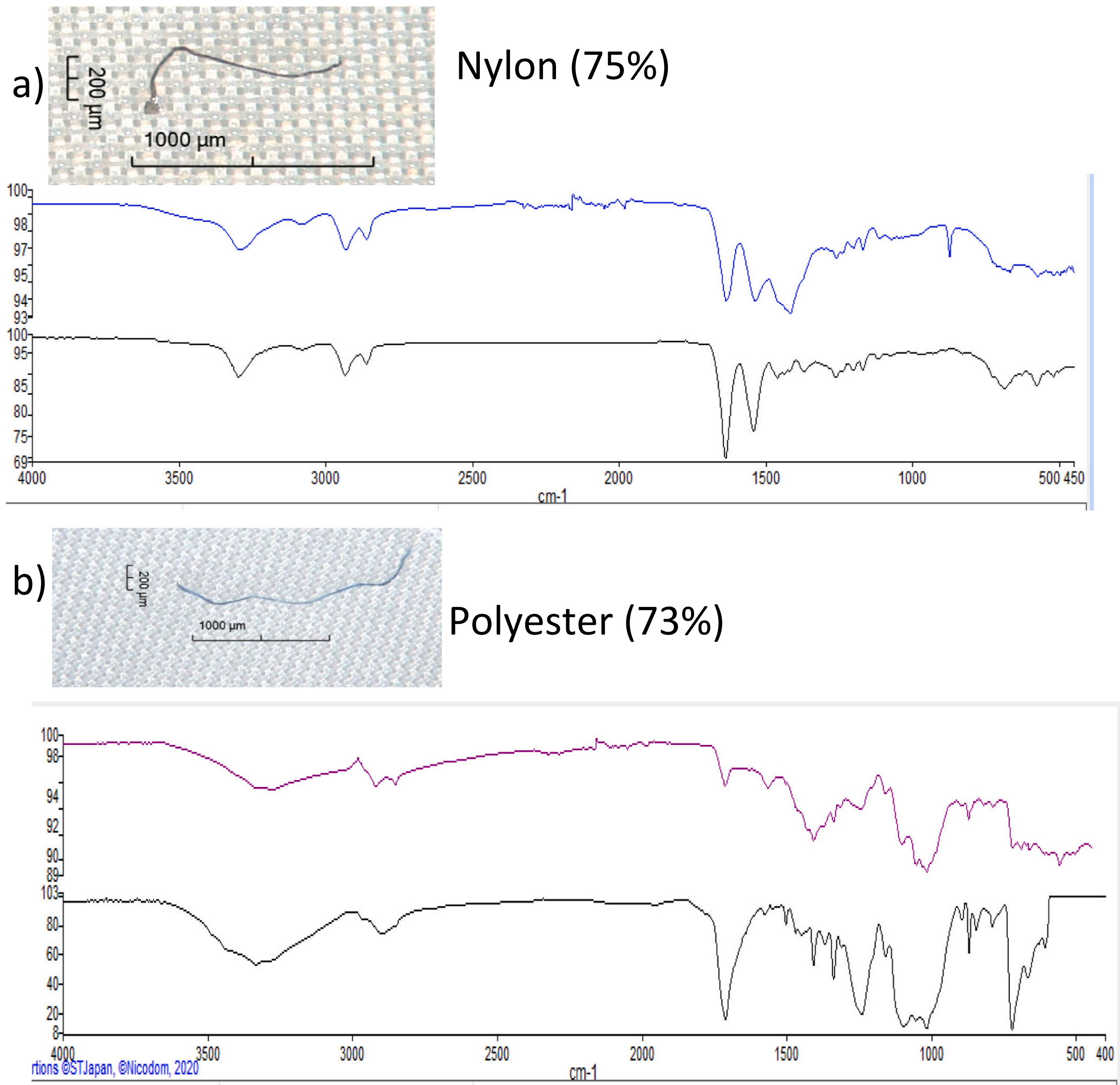

Fig. 2. Examples of microplastics scanned by the FTIR.

3. Results

From 1362 samples collected (all matrices), 4808 putative MPs were recorded in 85 % of samples processed. More than 95 % of potential MPs analysed were fibres, black (29 %) and blue (25 %). MPs between 1000 and 2000 μm (35 %), 2000–5000 μm (29 %) and 500–1000 μm (24 %) were the predominant sizes recorded. The average MPs recorded in matrices were 0.15 ± 0.01 MPs/L in water, 52.11 ± 3.51 MPs/kg dw in sediment, 2.30 ± 0.21 MPs/g stww in mussels, 0.14 ± 0.01 MPs/g stww in sea urchins and 1.61 ± 0.09 MPs/g stww in whelks. The percentage of samples that contained MPs for each sample type were 100 % for water and sediment, 91 % for mussels, 70 % for sea urchins and 91 % for whelk samples.

3.1. Water

Sixty water samples were collected across all sites, with a total of 908 putative MPs recorded, averaging 0.15 ± 0.01 MPs/L. For the respective locations sampled (Mouille Point, Three Anchor Bay and Camps Bay), MPs in water were significantly higher (U = 681, $p = 0.001$) at impact sites (0.18 ± 0.02 MPs/L) than control sites (0.12 ± 0.01MPs/L) as well as significantly higher (U = 694, $p = 0.001$) during winter (0.19 ± 0.02 MPs/L) than summer (0.11 ± 0.01 MPs/L) (Fig. 3a).

Samples were comprised of 94 % fibres and 3 % fragments and film, respectively. More film (12 %) and fragments (7 %) were recorded during summer at control sites (Fig. 3b). The dominant colours recorded were black (36.18 %) and blue (33.10 %) (Fig. 3c). The size category dominating samples were 2000–5000 μm (39.10 %) and 1000–2000 μm (35.67 %) (Fig. 3d). For both colour and sizes, the ratios did not differ extensively seasonally, nor between control and impact sites.

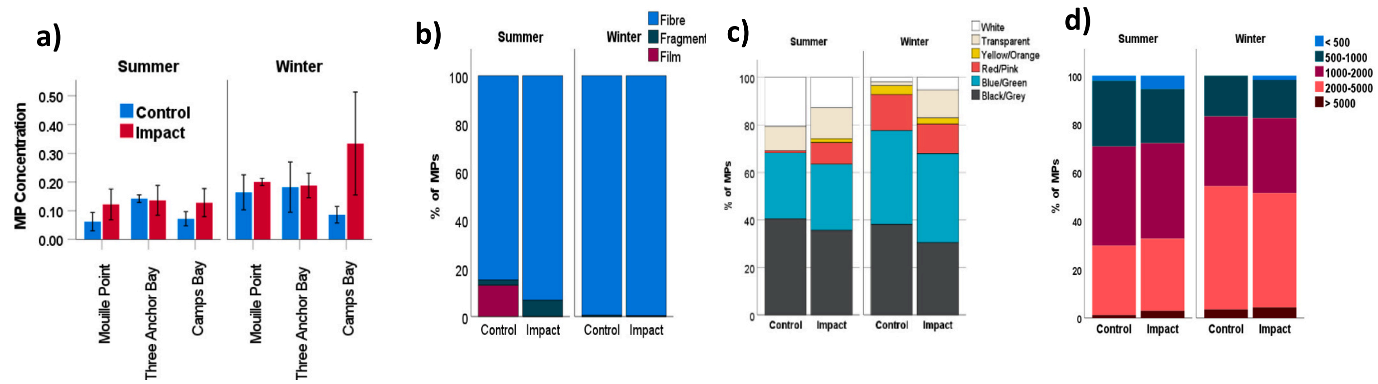

Fig. 3. a) The mean concentrations of MPs in water (MPs/L) at respective locations (Mouille Point, Three Anchor Bay and Camps Bay) based on season (summer and winter) and sites (impact/control) and percentage distribution of b) MP shape, c) colour and d) size categories at sites and seasons. Error bars represent SE. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Sediment

From 50 sediment samples processed for the study period, 523 MPs were recorded, averaging 52.14 ± 3.51 MPs/kg dry weight (dw). The MP concentrations at impact sites (63.29 ± 4.6 MPs/kg dw) were significantly (U = 510.5, $p = 0.001$) higher than control sites (35.40 ± 2.48 MPs/kg dw) (Fig. 4a). There were no significant differences in sediment MP concentrations between seasons (U = 364, $p = 0.31$). Despite no significant differences between seasons, impact site sediment MP concentrations during summer (59.20 ± 5.65 MPs/kg dw) were lower than winter (67.30 ± 7.32 MPs/kg dw). Fibres made up 97.13 % of sediment samples processed (Fig. 4b). Blue (31.12 %) and black (30.85 %) were the two colours predominantly found in sediment samples (Fig. 4c). The MP size categories that were predominant in sediment samples were 1000–2000 μm (40.10 %) and 500–100 μm (31.36 %) (Fig. 4d).

3.3. Mussels, sea urchins and whelks

A total of 1252 invertebrates (mussels = 444, sea urchins = 436 and whelks = 372) were processed to extract MPs. Based on weight, MP concentrations were highest in mussels (2.38 ± 2.31 MPs/g stww), then whelks (1.61 ± 0.09 MPs/g stww) and lowest in sea urchins (0.14 ± 0.01 MPs/g stww). Mussel (3.56 ± 0.35 MPs/g stww, U = 38,483, $p < 0.01$), sea urchin (0.18 ± 0.01 MPs/g stww, U = 31,520. $P < 0.01$) and whelk (1.74 ± 0.11 MPs/g stww, U = 19,787, $p = 0.02$) MP concentrations were significantly higher at impact sites than control sites (Fig. 5a).

Based on season, MPs in mussels (U = 4006.5, p < 0.001), sea urchins (U = 3801.5, p < 0.001) and whelks (U = 2035, p < 0.001) were significantly higher during summer than winter (Fig. 5b). The MP comparison between impact and control sites at Camps Bay (U = 4324, p < 0.001), Mouille Point (U = 5373, p < 0.001) and Three Anchor Bay (U = 2933, p = 0.012) in biota, were mainly found to be significant across mussels, with impact sites having higher concentrations (Fig. 5c). Based on intertidal/subtidal MP concentrations in invertebrates, mussels (U = 14,940, p < 0.01) and whelks (U = 4398, p < 0.01) were significantly higher in the intertidal than subtidal zones, with no significant difference in MP concentrations in sea urchins (U = 21,484, p = 0.08) between the two zones sampled (Fig. 5d).

Fibres made up most of the MPs found in mussels (92.41 %), sea urchins (95.74 %) and whelks (99.50 %) (Fig. 6a). The predominant colours found in biota were black in mussels (32.94 %), transparent in sea urchins (31.51 %) and blue in whelks (33.44 %) (Fig. 6b). The predominant sizes found in biota were 1000–2000 μm in mussels (35.49 %), 2000–5000 μm in sea urchins (33.67 %) and 1000–2000 μm in whelks (37.75 %) (Fig. 6c).

3.4. Characteristics of polymers in water, sediment and invertebrates

All putative particles scanned that had similarities <60 % were removed from the dataset. Thereafter, 6 % of all putative particles scanned were identified as natural, 62 % as semi-synthetic and 32 % as synthetic (Fig. 7a), indicating that 94 % of samples processed with the FTIR were confirmed as MPs. Natural particles, mainly fibres, that were removed from the data included cotton, wood and flax. The types of polymers classified as synthetic/semi-synthetic are indicated in Table 1.

Although concentrations of MPs were higher at impact than control

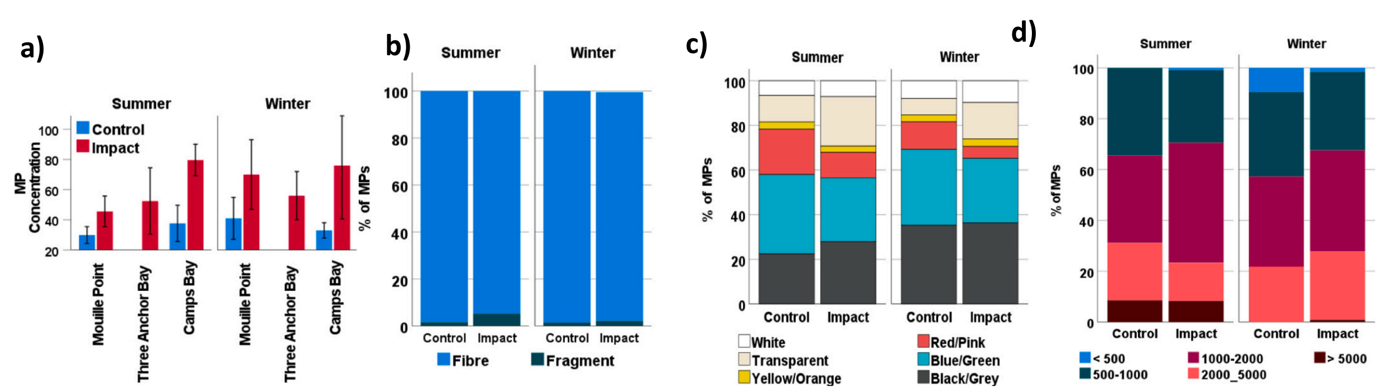

Fig. 4. a) Mean abundance of MPs/kg in sediment at impact and control sites across seasons (summer and winter) at Camps Bay, Mouille Point and Three Anchor Bay. Error bars represent ± SE. The percentage MPs found in sediment at sites and locations based on b) MPs type c) MPs colour and d) MP size categories. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

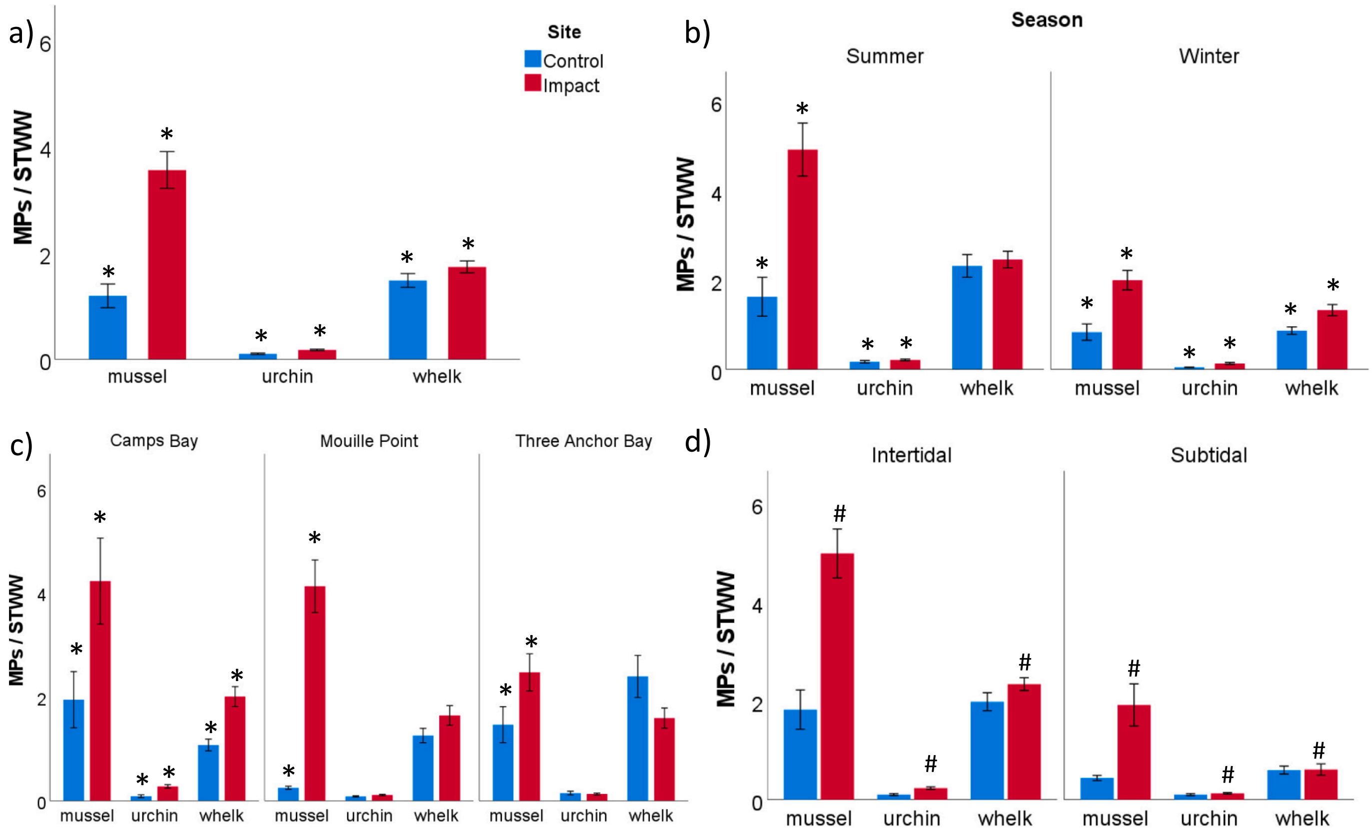

Fig. 5. a) The total mean abundance of MPs per STWW in fauna (mussels, sea urchins and whelks) across impact and control sites b) across seasons (summer and winter) c) at Camps Bay, Mouille Point and Three Anchor Bay d) In the intertidal and subtidal. Graphs are log scale. Error bars represent SE. Asterisks represent significance between impact and control sites and hash represents significance between impact intertidal and subtidal.

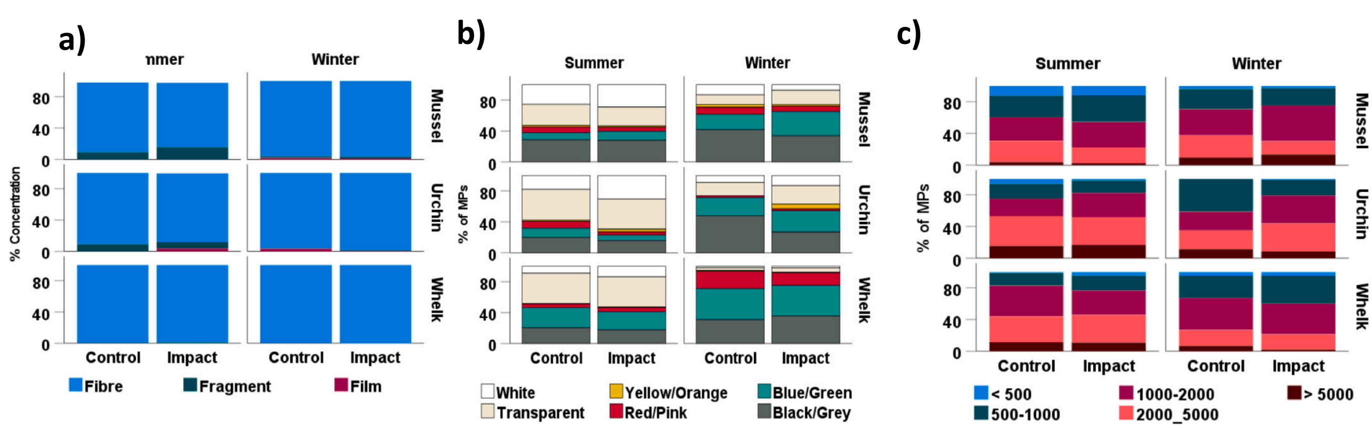

Fig. 6. : The percentage of MPs found in fauna (mussels, sea urchins and whelks) at all sites, zones and locations based on a) MP type b) MP colour and c) MP size categories. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sites, the percentages of MP shape were similar and mainly comprised of fibres (97 %). Hence, the results for polymers reflect that of mainly fibres. The percentages of fibrous polymers were not the same in respective matrices (water, sediment and invertebrates) at the 3 locations and seasons analysed. At Camps Bay PEST and Cotton Blends were the dominant polymers types across all matrices (Fig. 7b). Mouille Point had the most diversity of polymer types of the 3 sites sampled, with Cotton Blends the main polymers recorded in water, sediment and whelk samples. At Three Anchor Bay, Cotton Blends were mainly found in water, sediment and mussels and PEST mainly in whelks. Based on season, summer had the most diverse array of polymers and winter samples were mainly comprised of Cotton Blends in water, sediment, mussels and whelks, with sea urchins mainly comprised of PEST fibres (Fig. 7c).

4. Discussion

4.1. Factors influencing MP concentrations in Cape Town

Previous studies have shown that stormwater outlets are sources of MPs in coastal regions (Jannö, 2016; Jönsson, 2016; Preston-Whyte et al., 2021; de Villiers, 2018). This study provides baseline information that stormwater outlets in Cape Town, South Africa, are sources of MPs in the coastal environment. Based on seasons, MPs were higher in water

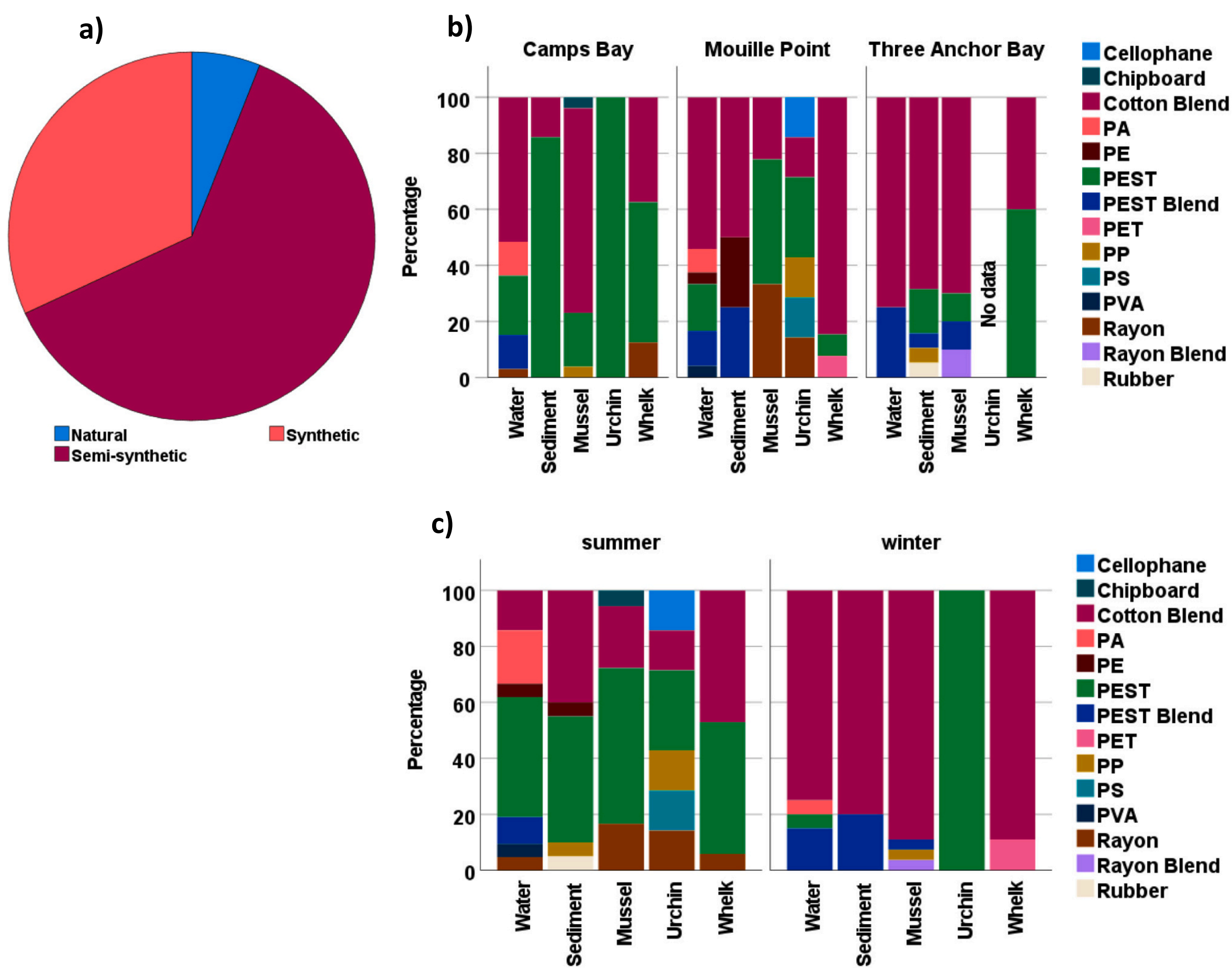

Fig. 7. The category and percentage of semi-synthetic and synthetic polymers a) based on sites b) and season c). See Table 1 for description of polymers abbreviations.

Table 1
Classification (Semi-synthetic or Synthetic) and abbreviations/terms of polymers.

Polymer classification	FTIR polymer (description)	Abbreviation/ term
Semi-synthetic polymer	Cellophane (Polypropylene/Cellulose Blend)	Cellophane
	Chipboard (Resin and wood)	Chipboard
	Cotton Blend (Cotton > 50 % and PEST < 50 %)	Cotton Blend
	PEST Blend (PEST > 50 % and Cotton < 50 %)	PEST Blend
	Rayon	Rayon
	Rayon Blend (Rayon/Polyester)	Rayon Blend
Synthetic polymer	Polyamide	PA
	Polyethylene	PE
	Polyester	PEST
	Polyethylene terephthalate	PET
	Polypropylene	PP
	Polystyrene	PS
	Polyvinyl acetate	PVA
	Rubber (Synthetic)	Rubber

and sediment during winter and MPs in mussels, sea urchins and whelks were higher in summer when compared to winter. We can assume that nearshore ocean dynamics such as upwelling and retention times play a role in the distribution and movement of MPs. A study by Schumann (1999) indicated that the west coast of South Africa region is dominated by upwelling during the summer (November to March), when strong southeasterly winds prevail. After an upwelling event, a relaxation period follows, with the decay in wind, thus allowing calmer and less mixing and allowing nearshore heating of surface water (Send et al., 1987). Therefore, these events can be linked to higher abundance of MPs found in biota in summer, as MPs can settle closer to the shore due to calmer conditions. The higher concentrations of MPs in water and sediment in winter can be associated with winter being the wet season in Cape Town. The higher rainfall results in stormwater systems carrying litter and MPs to stormwater outfalls. During the seasonal sampling, levels of precipitation when sampling took place during the summer sampling period were 0.1 mm–0.2 mm, while the winter sampling period had 0.4 mm – 8.4 mm of rainfall in Cape Town (worldweatheronline.com, 2022).

4.2. Origins of coastal MPs in Cape Town

Camps Bay recorded the highest mean MPs abundance compared to Mouille Point and Three Anchor Bay. It was visually observed that Camps Bay's stormwater outlet had a stronger flow rate of runoff compared to Mouille Point and Three Anchor Bay. This could have caused a higher input of MPs into the Camps Bay impacted site region. A study done by Klein et al. (2022) found that an increase in population caused higher concentrations of MPs within the intertidal water. Out of the three locations, Camps Bay does have the highest population, however, population numbers at Mouille Point were lower than Three Anchor Bay (https://census2011.adrianfrith.com). Although high plastic densities are linked with urban centres (Naidoo et al., 2015; Ryan et al., 2018), previous studies in South Africa have shown that plastic pollution is not correlated to population density (Nel et al., 2017). It should however be noted that coastal wastewater treatment works (WWTWs) that are present along the Cape Peninsula, discharges excessive amounts of effluent in the near shore and are sources of MPs (de Villiers, 2018).

4.3. MPs in water

The total abundance of MPs found in water was significantly higher at impacted stormwater sites compared to control sites (Fig. 2a). This illustrates that MPs are entering the coastal region via run off from stormwater outlets. A study by Nel and Froneman (2015) found extremely high concentrations of MPs in coastal surface waters (257.9 ± 53.36 to 1215 ± 276.7 m^{-3}) while impact sites from this study ranged from 0.16 ± 0.02 MPs/L to 0.23 ± 0.06 MPs/L (Table 2). When compared to other global studies reported in Table 2, this study had the lowest number of MPs found in surface waters.

MPs in water were higher during winter than summer, suggesting that the abundance of MPs increases in winter around stormwater outlets due to runoff entering the coastal area. Jiang et al. (2022) reported that MP concentrations in coastal waters were higher during the wet season when compared to the dry season. Similar results were reported by de Villiers (2018) for Cape Town, and the author suggested that stormwater outlets are potential sources of MPs in the marine environment during the first early winter rains (May–June). The characteristics of MPs reported in this study are similar to previous studies in the area where mainly black/blue fibres between 1000 and 5000 μm were recorded (Nel and Froneman, 2015).

At Camps Bay, Three Anchor Bay and Mouille Point, FTIR scans indicated that Cotton Blend fibres were the predominant polymers present in water. The main products of this semi-synthetic polymer are clothing (cotton and PEST blends). Since sites are located adjacent to residential areas, high amounts of fibres can be expected. Browne et al. (2011) reported that fibres generally originate from inland water sources due to domestic washing. Washing of a single garment is estimated to produce thousands of fibre particles that can released into wastewater systems such as stormwater pipes (Geyer et al., 2017).

4.4. MPs in sediment

Sandy beaches are one of the most studied environments when it comes to MPs research (Pinheiro et al., 2019). MPs on the strandline represents MPs that were recently deposited on the beach from the previous high tide. MPs in sediment at impact stormwater sites was higher than control sites (Fig. 3a). This suggests that MPs from stormwater outlets are sources of MPs to intertidal waters and incoming tides transport floating MPs to nearby strandlines. The mean abundance of sediment MPs at Camps Bay, Mouille Point and Three Anchor Bay was lower, or similar to other studies across the globe (Table 2). The concentrations of MPs in sediment at the Camps Bay impact site (77.81 ± 8.72 MPs/kg dw), was lower than reported in a study by de Villiers' (2018) (101 ± 147 (SD) F/dm^3). Like water, sediment MP concentrations were higher in winter when compared to summer. Jiang et al. (2022) also found that sediment MP concentrations were higher during the wet season. Precipitation is most likely the key reason for the increase of MPs in sediment, as more runoff is likely to enter the coastal zone. MPs are likely to be washed up and settle in sediment. Due to MPs being ubiquitous in water during winter, tides wash MPs into the intertidal zone where sediment particles can trap MPs from washing back inshore. MPs that are often trapped in sediment can cause a blockage of water filtration, thus decreasing nutrient availability to biotas and can even affect ambient temperatures (Lamprecht, 2013). Like

Table 2
Mean abundance of MPs in water, sediment, mussels, sea urchins and whelks across various regions.

Country/region	Mean abundance (SE)	Reference
Surface seawater (per litre)		
Camps Bay (Impact), South Africa	0.23 ± 0.06	This study
Mouille Point (Impact), South Africa	0.16 ± 0.02	This study
Three Anchor Bay (Impact), South Africa	0.16 ± 0.02	This study
South Africa	257.9 ± 53.36–1215 ± 276.7 m^{-3}	(Nel and Froneman, 2015)
South Australia	2.95 ± 0.42–16.31 ± 2.42	(Klein et al., 2022)
Jiaozhou Bay, China	46 ± 28	(Zheng et al., 2019)
Yellow Sea, China	130 ± 200	(Sun et al., 2018)
Northern Yellow Sea, China	500 ± 300	(Zhu et al., 2019)
Beach sand (particles per kg dw)		
Camps Bay (Impact), South Africa	77.81 ± 8.72	This study
Mouille Point (Impact), South Africa	57.81 ± 7.19	This study
Three Anchor Bay (Impact), South Africa	54.26 ± 6.42	This study
Cape Peninsula, South Africa	101 ± 147 (SD) F/dm^3	(de Villiers, 2018)
Qinzhou Bay, China	20–12,852	(Li et al., 2018)
Fishing port beach, China	180–457	(Pervez et al., 2020)
Marina Beach, India	20–1540	(Sunitha et al., 2021)
Gulf of Thailand, Thailand	420	(Bissen and Chawchai, 2020)
Koksijdde-bad, Belgium	56.9–102.1	(Claessens et al., 2011)
Groenendijk, Belgium	48,7–156.2	(Claessens et al., 2011)
Mussels (particles per gram stww)		
Camps Bay (Impact), South Africa	4.2 ± 0.83	This study
Mouille Point (Impact), South Africa	4.12 ± 0.51	This study
Three Anchor Bay (Impact), South Africa	2.47 ± 0.36	This study
South Australia	6.67 ± 1.25	(Klein et al., 2022)
South Africa	2.33 ± 0.2	(Sparks, 2020)
China	1.52–5.36	(Qu et al., 2018)
Belgium	2.6–5.1 (10 g STWW)	(de Witte et al., 2014)
Germany	0.36 ± 0.07–0.47 ± 0.16	(Van Cauweberghe and Janssen, 2014)
Whelks (particles per gram stww)		
Camps Bay (Impact), South Africa	2.00 ± 0.19	This study
Mouille Point (Impact), South Africa	1.64 ± 0.19	This study
Three Anchor Bay (Impact), South Africa	1.58 ± 0.19	This study
Persian Gulf	12.8–20	(Naji et al., 2018)
Sea urchin (particles per gram stww)		
Camps Bay (Impact), South Africa	0.28 ± 0.03	This study
Mouille Point (Impact), South Africa	0.11 ± 0.01	This study
Three Anchor Bay (Impact), South Africa	0.13 ± 0.19	This study
Greece	1.95 (σ = 1.70)	(Hennicke et al., 2021)
Tajao and El Poris, Spain	9.2 ± 3.0 (SD)–10.0 ± 4.5(SD)	(Sevillano-González et al., 2022)
North coast, China	2.20 ± 1.50–10.04 ± 8.46 (SD)	(Feng et al., 2020)

water, the main MP type found in sediment was fibres, which made up 97.13 % of MP particles found. A previous study by Martin et al. (2017) also found a higher percentage of fibre MPs in sediment core samples, which made up 85 % of MPs, of which blue was the dominant colour. The main colour of MPs found in sediment of this study were blue and black, with a size range of 1000–2000 μm and 2000–5000 μm. Cotton blend was the most common polymer in sediment at Mouille Point and Three Anchor Bay, similar to that of water sampled. This suggest that MPs in water are settling in sediment at impact sites which supports the postulation that stormwater outlets are sources of MPs in coastal sediment (Geyer et al., 2017).

4.5. MPs in mussels, sea urchins and whelks

Invertebrates sampled at impact stormwater sites had higher MPs in their tissue than individuals from control sites (Fig. 4a), with mussels having the highest concentrations of MPs. MPs in mussels were higher at impact sites during the summer than winter. This study found that 90.7 % of mussels, 69.7 % of sea urchins and 91.1 % of whelks that were sampled had MP particles. The prevalence of MPs in coastal invertebrates is higher than elsewhere (Table 2). For example, studies found MPs comprising up to 47.5 % of mussels sampled from coastal waters in China and the Mediterranean Sea (Li et al., 2016).

It is postulated that since mussels are non-selective filter-feeders, they assimilate more MPs when compared to other feeding groups such grazers (sea urchins) and predators/scavengers (whelks) (Fig. 4a). According to Setala et al. (2016), filter-feeding bivalves tend to ingest significantly higher amounts of MPs beads when compared to other feeding groups. Non-selective filter-feeders filter most particles in the water column based on size, making them susceptible to MPs contamination (Moore et al., 2001). The average MPs in mussels at impact sites was notably higher compared to a study by Sparks (2020) on mussels in the same area. Sparks (2020) found an average of 2.33 ± 0.2 MPs/g stww in mussels, also mainly fibres, while the highest average of MPs in mussels found at impact sites in Camps Bay were 4.20 ± 0.36 MPs/g stww. The lowest MP concentrations at the Three Anchor Bay impact site, also had higher MPs (2.47 ± 0.36 MPs/g stww) when compared to the study of Sparks (2020). When compared to other countries, the abundance of MPs in mussels for this study were more or less in the same range or lower, with the exception of a study done on mussels in Germany by Van Cauweeberghe and Janssen (2014) that had an abundance of 0.36 ± 0.07–0.47 ± 0.16 MPs/g stww (Table 2).

Like mussels, urchins are non-selective feeders. However, they graze on algae on the benthos, so digesting MPs would depend on the availability and the ability of MPs to attach to either rocks or algae (Sevillano-González et al., 2022). According to a study by Barkhau et al. (2022), most bivalve filter-feeders like mussels that are found along rocky shores are susceptible to ingesting MPs particles due to their feeding strategy. Piarulli et al. (2020) and de Barros et al. (2020) suggest that the organism's feeding mode can be linked to the amount and the type of MPs particles that are ingested and not necessarily on the type of habitat or trophic group, which is why sea urchins that are non-selective grazers have a lower mean abundance of MPs compared to mussels. According to a study by Mudd et al. (2010), macroalgae species found on rocky shores often trap MPs due to the complex topography, thus making it available to be ingested by grazers like sea urchins. Compared to other studies done by Sevillano-González et al. (2022) in Spain (9.20 ± 3.0 (SD)–10.0 ± 4.5(SD)) and Feng et al. (2020) in China (2.20 ± 1.50–10.04 ± 8.46 (SD)), this study found a considerably lower number of MPs in sea urchins, with the highest abundance at the Camps Bay impact site (0.28 ± 0.03 MPs/g stww).

Whelks had the second highest concentrations of MPs based on both seasons and locations (Fig. 4). Whelks potentially predate on mussels and other invertebrates in rocky shores and hence the abundance of MPs in whelks may be directly related to MPs in prey consumed (Hunt and Scheibling, 1998; Ekaratne and Goonewardena, 1994). A study by Naji et al. (2018) in the Persian Gulf on the *Thais mutabilis* (a predator snail like the *Burnepena* sp.) reported an average of 5.50 ± 2.70 MPs/g stww, compared to this study where 1.74 ± 0.11 MPs/g stww was recorded. The results suggested that MPs in prey consumed by whelks directly influence the concentrations of MPs in whelks. Like most samples, whelks had a high percentage of fibres in them and an experimental study done by Xu et al. (2022) found more fibres than fragments in whelks when offered both MP types in long exposure experiment periods.

The mean MPs found in fauna samples during the summer were higher compared to samples found during winter (Fig. 4b). This is the complete opposite result compared to water and sediment. It was expected that, with the increase of MP load in water, there would be an increase in the MPs in biota, as Qu et al. (2018) found an increase in MP load in mussels with the increase in MP load in water. It is expected that more pollutants are released during the rainy season, but flushing is also stronger during this period (Du et al., 2020). Taylor et al. (2011) therefore stated that the release of runoff is not necessarily linearly proportional to the total loading of pollutants. It could be suggested that the morphodynamics of coastal areas, with the influence of stormwater outlets or river systems, play a major role in the spatial distribution and concentrations of MPs (Pinheiro et al., 2019), as various studies have found the loading to increase during winter and others in summer. Although the winter sampling period had a higher precipitation than the summer period, retention times of bays are much longer due to calmer conditions allowing less flushing to occur (Taylor et al., 2011). Longer retention times allow pollutants such as MPs to settle in bays, causing them to be more ubiquitous. Upwelling periods in South Africa tend to be followed by long relaxation periods that brings about calmer sea conditions, allowing for MPs to settle. The accumulation of MPs also depends on ejection and excretion of these organisms, as the uptake minus removal activity makes up the concentration of MPs found within the body tissue (Ding et al., 2021; Li et al., 2018). Fibres, being the main type of MPs found in this study, are said to be retained longer within organisms causing accumulation of MPs (Mayoma et al., 2020).

Biota intertidal samples were found to have higher mean values of MPs compared to samples in the subtidal zones (Fig. 4d). One reason for the intertidal having a higher influence of MPs distribution is because stormwater outlets are directly adjacent to the intertidal area and runoff is directly into the intertidal zone. Another reason is that MPs, depending on the type, are buoyant and therefore will not reach the benthos in the subtidal where invertebrates were collected. Sampled areas, however, are prone to a lot of mixing and turbulence which could allow MPs to reach the benthos.

Fibres were the predominant type of MPs found in all fauna samples and these results are similar to that reported elsewhere in the world (Doyle et al., 2019) and previously in the same area (Sparks, 2020). Black, blue and transparent were the most common colours found in mussels and whelks and transparent, black and white in sea urchins. Previous studies on sea urchins also found high amounts of blue, black or transparent MPs in sea urchins (Hennicke et al., 2021; Sevillano-González et al., 2022; Feng et al., 2020). The most common sizes of fibres that were found in fauna samples were in the range of 2000–5000 μm,1000–2000 μm and 500–1000 μm. The length of MPs is in the same class range of previous studies done on mussels, sea urchins and whelks (Sevillano-González et al., 2022; Feng et al., 2020).

Most invertebrate samples consisted of PEST and Cotton:PEST blends which may settle to the benthos over time (due to biofouling). The ratio of polymers in invertebrates at Camps Bay and Three Anchor Bay were similar to water and sediment and we can assume that a lack circulation at these sites facilitated the uptake from stormwater outlets (Fig. 1). This pattern was not observed at Mouille Point, a site along the northern coastline that was most exposed to the open ocean and not protected. Mussels and sea urchins had the most diverse record of polymers for all sites sampled, which was particularly evident in summer. Polymer diversity was also higher in summer than winter (Fig. 7c). As coastal invertebrates are actively feeding in summer (reproductive season) the diversity of polymers may also be reflecting the uptake of available MPs during summer. According to Taylor et al. (2011), MPs in stormwater outlets are not linearly proportional to total contaminant loads. The uptake of diverse polymers by invertebrates during summer hence requires further investigation.

5. Conclusions

The Cape Peninsula of Cape Town is a broad stretch of coastal land that is impacted by numerous stormwater outlets that have unknown catchment areas. These stormwater outlets are extremely close to one another, which made site selection extremely difficult for control sites. However, it was clear in our results that stormwater outlets are sources of MPs for coastal regions, as impact sites at Camps Bay, Mouille Point and Three Anchor Bay had higher MP concentrations when compared to sites that were ±200 m away from impact stormwater outlets. Higher MPs were reported in winter (rainy season) in water and sediment. Higher MPs recorded in mussels, sea urchins and whelks during summer and the intertidal were also influenced by stormwater outlets. Filter feeders being mussels were found to have higher concentrations of MPs compared to grazers (sea urchins) and carnivores (whelks) and ideally is a better bioindicator due to the results. Further monitoring of stormwater outlets is advised to assess the type of MPs entering the coast at local scales as this may provide better understanding of the impacts of MPs and the development of management strategies regarding coastal stormwater systems.

CRediT authorship contribution statement

Rushdi Ariefdien: Conceptualization, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Project administration. **Maya Pfaff:** Conceptualization, Resources, Writing – review & editing, Supervision. **Adetunji Awe:** Methodology, Data curation, Writing – review & editing. **Conrad Sparks:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Funding acquisition, Project administration.

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

Data will be made available on request.

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