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Research article

Microplastic concentrations and risk assessment in water, sediment and invertebrates from Simon's Town, South Africa

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ABSTRACT

Plastic pollution is an ever-increasing threat globally and poor waste management in South Africa has caused an increase in plastic leakage into the environment. Plastic waste in the environment are categorized according to size and plastic particles smaller than 5 mm in size are regarded as microplastics (MPs), and little to no research has been done on MPs pollution within the marine coastal environment and rocky shores in South Africa. Sampling was done in February 2020 at a rocky shore within Simon's Town Marina, Cape Town. MPs were extracted from collected water (n = 5), sediment (n = 5) and biota (n ≤ 30) samples. The extracted MPs were further classified based on shape, colour, size and an attenuated total reflectance Fourier-transform infrared (ATR-FTIR) instrument was utilized for polymer type identification The risks posed by MPs because of concentration at which they occurred and chemical composition were assessed in all the sample types. As expected, MPs were higher in sediment (38 ± 2 MP/kg) than in water (0.37 ± 0.06 MP/L) as the area has low water energy, allowing MP particles to settle within the sediment. Filter-feeding organisms had the lowest average MP particle concentrations (0.28 ± 0.04 MP/g) but displayed the highest variation of MP particle colours due to the non-selective feeding strategy, where other feeding strategies ingested mostly black/grey particles. The dominant MP size was between 100 μm and 500 μm in size for all samples combined, with the most abundant MP polymer type being nylon (27.27 %), polyethylene terephthalate (PET) (18.18 %) and natural MP particles such as cotton (18.18 %). The risk assessment indicated that polymer type poses a greater risk of MP pollution than MP concentrations.

1. Introduction

Plastic enters the terrestrial and aquatic environment through littering and poor waste management of plastic waste [1]. The plastic debris in terrestrial environment gets blown around by the wind and lands in rivers, eventually flowing into the marine environment [2]. The release of plastic waste into the marine environment could also be directed from marine-related activities, such as plastic waste from boats, ships, and recreational activities in the coastal region. Plastic waste also travels to the marine environment through marine outfall pipes, which disposes wastewater from wastewater treatment works (WWTWs) and stormwater drains to the ocean [3]. While large plastic debris can easily be disposed of, microscopic plastic particles are difficult to detect and difficult to remove from

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waste and these microscopic particles eventually enters the marine environment.

Microplastics (MP) are microscopic plastic particles smaller than 5 mm [1]. A lot of these microscopic particles are manufactured at this size, called primary MPs, as it serves as a basic plastic base and is melted and moulded into common plastic items. The microscopic pellets can also be used in abrasives in everyday products such as toothpastes and face washes, as well as in industrial activities [1]. Secondary MPs are microscopic plastic particles that have been fragmented into <5 mm particles from a larger plastic source [4]. The process of mechanical fragmentation is sped up when plastics spend a prolonged period exposed to sunlight, weakening the structural integrity of the plastic [5]. Plastic debris poses short- and long-term negative effects to marine organisms, human health, aesthetics, and tourism [6]. The longevity of plastic makes it a significant problem within the marine environment, as the plastic particles will persist in the marine environment for a long time [7].

Microplastics tend to float in the upper layer of the water column due to their buoyant nature. This also allows them to be dispersed fairly quickly with waves, wind and ocean currents [7]. Some plastics, such as polyvinyl chloride (PVC), are negatively buoyant and do sink [6,8]. This makes MPs biologically available to a large variety of organisms across the entire water column. Unlike mobile organisms, sessile invertebrates within the rocky shore cannot move away from polluted areas to find a cleaner and healthier habitat [9].

The rocky shore is one of the major crossover ecosystems between the terrestrial and aquatic environments, to the marine environment. An array of plant and animals inhabit this area of the marine environment and are exposed to a diurnal tidal cycle in South Africa, being submerged in water and exposed twice a day [10]. Rocky shores have three distinct zones which dominate the shore, the Littorina, Balanoid and the intertidal zones.

In the lowest zone of a typical temperate region rocky shore in southern Africa, the intertidal zone is covered with water for majority of the day [11]. This zone is dominated by larger seaweeds, such as *Laminaria pallida* and *Ecklonia maxima*, as well as small primary consumers such as sea urchins and some whelk species [11]. They graze on the seaweeds and other pieces of seaweeds floating in with the water column that has been broken up by the strong waves and currents. The Balanoid zone is dominated by barnacles and other colonial organisms as well as grazers, with smaller bushy seaweeds, such as *Ulva* spp. and *Porphyra capensis*. Other prominent organisms in this zone are the blue (*Mytilis galloprovincialis*) and brown (*Perna perna*) mussels. Sea squirts such as *Pyura stolonifera* and sea anemones also mostly inhabit the Balanoid zone. The Littorina zone is the uppermost region of the rocky shore and named after a marine mollusc, *Littorina littorea*. Generally, the zone is only completely covered during spring tides and receive splashes during the neap tidal cycles. This zone is inhabited by opportunistic feeders that feed on nutrients washed out by the rising tide and the waves washing out [10].

South Africa is ranked 11th highest globally for plastic waste generation in 2010, producing 0.63 million tons of plastic waste, of which marine plastic contribute as much as 0.25 tons [12]. South Africans use up to 50 kg of plastics daily, and the South Africa produced 42 million tons of general waste in 2017, of which 5 % (2.2 million tons) was plastic waste. Of that 5 %, 15 % was recycled and the remaining plastic stayed in landfill sites around the country [12].

South Africa has poor wastewater infrastructure that cannot be managed effectively to cope with an increasing population [13]. Only a fraction of the wastewater is treated before discharge and the percentage of treated wastewater has decreased with increased population size [13]. Therefore, WWTWs are large contributors of MPs into the coastal environment. Textiles, medicinal, cosmetic, and industrial MPs can land in the coastal marine environment through WWTPs [14–16].

Due to South Africa being a developing country, effective waste management is not a high priority for the government [17]. The Western Cape is one of the largest contributors to waste production within South Africa, behind Gauteng and KwaZulu-Natal [18], with twenty per cent of the country's waste can be attributed to the Western Cape, equating to 8.4 million tons of general waste in 2017 [18]. The largest metropole within the Western Cape is Cape Town [19], making Cape Town unarguably the largest contributor of waste within the province.

Ingested MPs have negative effects on organisms, including intestinal obstruction, false satiation, inflammation, diminished energy reserves, reduced survival rate, hindrances to growth and reproduction, and delayed development of larvae [8]. Although MPs generally float in the water column or settle in marine sediments, the behaviour of MPs within a rocky shore is relatively unknown. Therefore, it is vital to investigate the concentrations of MPs in various marine coastal invertebrates that use different feeding strategies. This will not only indicate what organisms are vulnerable to MP ingestion, but it will also indicate where most MPs are within the rocky shore.

Since rocky shore invertebrates are sedentary, they are constantly exposed to MPs within the localised region. Therefore, rocky shore invertebrates are ideal candidates to use as biomonitors for MP contamination. Hence, the aim of the study was to measure the concentrations and characteristics of MPs in water, sediment and selected invertebrate biota in a rocky shore in Simon's Town, Cape Town. The selected invertebrates were representative of different feeding groups of filter-feeders (mussels, *Mytilus galloprovincialis*; redbait, *Pyura stolonifera*), grazers (cushion stars, *Parvulastra exigua;* limpets, *Scutellastra longicosta;* winkles, *Oxystele tigrana*) and predators/scavengers (starfish, *Marthasterias glacialis*; whelks, *Burnupena lagenaria*). The objectives of the study were to characterise MPs in different matrices in a marina in Simon's Town, South Africa and to assess the environmental risks posed by polymers recorded in the respective matrices measured.

2. Materials and methods

2.1. Study area

False Bay (Fig. 1) is a calm and southward facing Bay on the southern point of the Cape Peninsula. The area extends from Cape Point in the west to Cape Hangklip in the east, and strong southerly winds are responsible for the clockwise cyclonic circulation within the bay [20]. The water circulation is driven by the dynamics of the winds within the bay. In summer, the circulation is controlled by predominantly south-easterly winds and by north-westerly winds in the winter [20]. The Summer months produce high air temperatures that increase sea surface temperatures. The southerly winds in move surface waters in a westerly direction, aiding to the cyclonic movement of water throughout the bay. There are various potential sources of MP contamination throughout the Cape Peninsula coastline. These include seasonal rainfall, water circulation, waste management, harbour-related activities, waste-water treatment works (WWTW's), outfall and stormwater pipes [21].

Simon's Town is a is approximately 40 km from the City of Cape Town and an important maritime area and port for the South African navy fleet [22]. Simon's Town is a semi-enclosed bay that is generally shallow throughout the water column. The general wind pattern that occurs offshore in the mouth of the greater False Bay causes increased wave height and storm surges. With the general flow pattern being clockwise throughout the greater False Bay area, cold water flows past Simon's Town from the south-west regions of False Bay, bringing potential pollutants from more southern regions of the bay [21]. Simon's Town is an urbanised area, mainly populated with residents. It is also a popular tourist attraction, with high pedestrian traffic and beachgoers during the summer season. This provides a potential source of pollutants. Within Simon's Town Marina, there are recreational activities such as restaurants and bathing sites, as well as industrial activities in the form of boat building and maintenance. There is also a wastewater treatment facility near the sampling site, as well as outfall pipes carrying treated wastewater into the ocean. Several stormwater drains also lead into the bay.

2.2. Field sampling and laboratory processing of water and sediment samples

Water and sediment samples were collected during February 2020 from Simon's Town Marina (34°11′32.8″S 18°25′59.4″E) (Fig. 1). All sampling equipment was rinsed with site water before use. This was to eliminate any potential microplastic cross contamination between sites. All glassware and metalware were autoclaved before use. All equipment was also rinsed with reverse osmosis (RO) water that was filtered through a 10 μm mesh before use.

Water at 50 cm below the surface and bulk sampling of five separate 20 L replicates were taken, filtering each though a 250 μm metal sieve (equates to 100 L of water sampled at the site). The particles on the sieve were rinsed into a clean falcon tube and transported to the laboratory for further analysis. Once in the laboratory, water (with the suspected MPs particles) was transferred from the falcon tubes into glass jars, the falcon tubes being rinsed thrice with10 μm filtered RO water to ensure no MPs residue was left

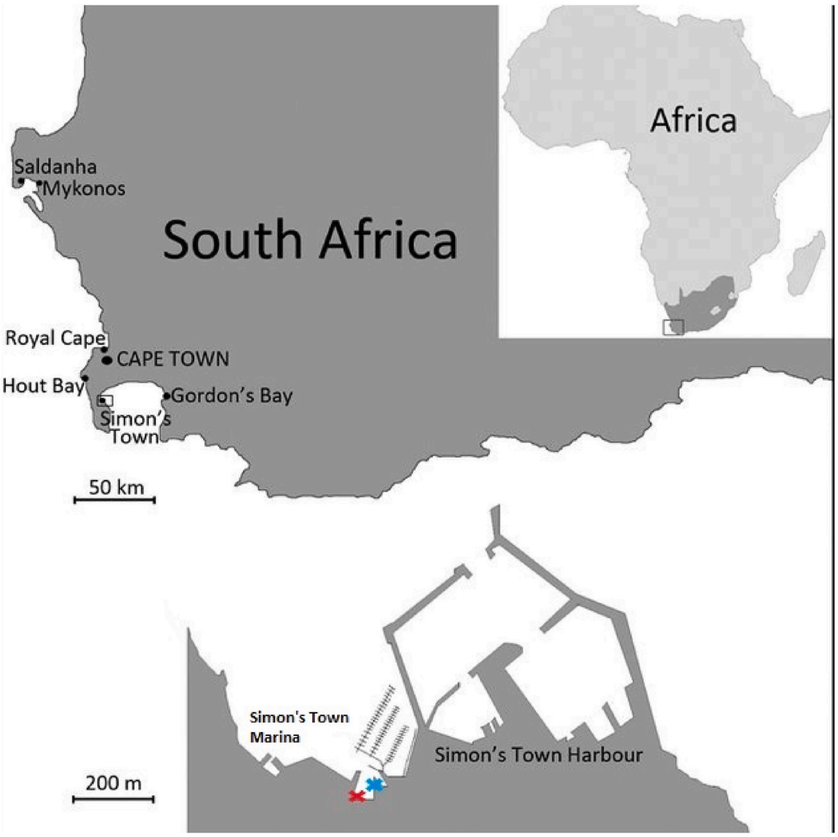

Fig. 1. Map of sampling site, Simon's Town, Cape Town (the red cross indicates the location of the sampling site, and the blue cross indicates the location of the boat building/maintenance facility).

in falcon tubes. To the transferred water, 10 % KOH (filtered through a 10 μm mesh) was added and the solution placed in an oven (model DHG 9070A) at 50 °C for 24 h to remove any biological material. Once the sample had digested, the digestate was processed through a Buchner filtration setup system, fitted with a 20 μm mesh. The glass jar and the Buchner funnel were rinsed thrice to ensure all potential MPs are transferred onto the mesh. The mesh was then placed in a clean Petri dish and left to dry until MPs analysis is conducted.

The top 5 cm of marine sediment was collected at the most recent strandline adjacent to the rocky shore, using a 0.25 m × 0.25 m quadrat. Five replicates, each spaced 5 m apart (parallel to the coastline) were collected with a metal spoon and placed into pre-cleaned glass jars. The obtained sediments were then transported to the laboratory. Once in the laboratory, at least 200 g of sediment was weighed using a top-balance (Highland® portable precision balance-HCB 302) and transferred into an aluminium container using a metal spoon. Aluminium foil was used in covering container, then the sediment sample was placed in the oven at 50 °C until a constant weight. Of dried sediment, 100 g t was utilized for MP extraction.

The sediment in the jar for MP analysis was digested by adding 10 % KOH solution, following the same method used for water samples. The ratio of sediment to KOH solution was1:3, and digestion occurred at 50 °C for 24 h in the oven. Once digested, hypersaline solution was added (10 μm filtered solution of 360 g of salt per 1 L of RO water). The sediment was stirred for 5 min with a metal spoon and left to settle for 15 min. The supernatant was then processed through the Buchner filtration setup system as described for water samples. Each sample went through three consecutive hypersaline extraction cycles. After the sample was extracted three times, the mesh was carefully removed from the filtration setup, placed into pre-cleaned Petri dish to dry until the MPs analysis.

2.3. Processing of biota

At least 20 specimens were collected per species at the site (Table 1). Specimens were put into plastics ziplock bags and kept on ice in a cooler box for transportation back to the laboratory.

Once in the laboratory, the total whole weight (including shell and wet soft tissue weight - TW), was measured in grams (g). Subsequently, the wet soft tissue, carefully separated from the whole organism, was weighed separately to determine the wet soft tissue weight (STW) in grams (g). Where applicable, the total shell length (TL) was also measured in millimeters (mm) using a Vernier calliper. The soft tissue was placed in a glass jar and digested in a 10 % KOH solution (same preparation method as before). The ratio of the tissue to KOH was 1:2 (one-part tissue to two-parts KOH), and the digestion also occurred at 50 °C for 24 h in the oven. Once digested, the contents in the jar were processed through the Buchner filtration setup system and extracted MPs stored until the MPs analysis as described for water samples. The jar and the Buchner funnel were also rinsed thrice with 10 μm filtered RO water, onto the mesh to ensure all potential MPs from the samples were extracted.

2.4. Microplastic visual identification and FTIR analysis

The visual identification and documentation of MPs followed a previously established method [1]. To summarize, MPs from our samples were visually classified using a microscope (Zeiss DV 4 dissecting microscope at 100x magnification). The recorded categories of MPs were determined based on their type, colour, and size [23]. The quantification and classification of MPs underwent peer review to ensure the accuracy of data.

Once the MPs were isolated and identified, 10 % of the total number of MPs (selected particles also had to be bigger that 500 μm in size) were scanned using an Attenuated Total Reflectance (ATR) Infrared spectrometer, specifically, the PerkinElmer Spectrum Two. This method was previously reported in our study by Sparks and Awe (2022) [24]. The FTIR spectra of the MPs were recorded over the range of 4000 and 450 cm^{-1} wavenumber with resolution set to 4 cm^{-1}, data interval set to 1 cm^{-1} and the number of scan accumulations set to ten. Prior to scans, the crystal surface of the ATR was cleaned with isopropanol and background correction was performed. Additionally, to prevent cross contamination between scans, the ATR crystal area of the instrument was cleaned with isopropanol before each MPs scan. The instrument utilized was equipped with an ST Japan Library and a Perkin Spectral Library, for MP polymers identification.

2.5. Statistical analysis

The statistical analysis was performed using the IBM SPSS Statistics V28 software package. The data for MPs in water are presented as MP per litre (MP/L) while for sediment samples, they are presented as MP per kilogram (MP/kg). For biota data, the MPs count was

Table 1
Organisms sampled at Simon's Town Marina.

Feeding strategy	Organism	Common name (referred to in text)	Number of samples (n)
Filter feeder	*Mytilus galloprovincialis*	Mussel	30
	Pyura stolonifera	Redbait	27
Grazer	*Parvulastra exigua*	Cushion star	23
	Scutellastra longicosta	Limpet	30
	Oxystele tigrana	Winkle	30
Scavenger/predator	*Marthasterias glacialis*	Starfish	25
	Burnupena lagenaria	Whelk	30

expressed as MP per individual (MP/I) and MP per gram (MP/g) of the wet soft tissue weight (STW). To assess the normality of the data, the Kolmogorov-Smirnov test was conducted, utilizing data skewness in conjunction with histograms. It was found that data was not normal and non-parametric tests for significance was undertaken using Mann-Whitney tests U tests (tested for significant difference between two groups) and Kruskal-Wallis H tests (tested for significance between 2 or more groups; H = Degrees of freedom, number of groups - 1). The variance of data was presented as the standard error around the mean (±SE) and the significance level was $p < 0.05$. A Spearman-rank correlation was conducted in within grazers to determine the relationship between the total number of microplastics, the soft tissue wight (g) and the total weight (g).

2.6. Microplastics risk assessment

The risks associated with the detected concentration and chemical composition of microplastic in this study, were assessed based on the method utilized in our previously reported study [23]. The risk assessment utilizes indices for comparative assessments of the potential risks of MPs in the environment and the risk categories in relation to the indices are presented in Table 2.

The enrichment of MPs in our samples at the study site was assessed through the MPs contamination factor (MPCF) index, which was determined using Equation (1).

$$MPCF_i = \left(\frac{C_{microplastic}}{C_{baseline}}\right) \quad \text{>Equation 1}$$

Where the $C_{baseline}$ value is the background MPs concentration; the background concentration utilized here for water was that previously recorded in Rooi Els, for sediment that in Simon's Town and for echinoderm that in Rooi Els samples [23] and this method has been adjudged acceptable [25].

For the assessment of MP pollution index (MPPLI), Equation (2) below was utilized.

$$MPPLI_{site} = \sqrt[2]{MPC_{Fil} \times MPC_{Film}} \quad \text{>Equation 2}$$

MPC_{Fil} and MPC_{Film} represent the microplastic contamination factors (MPCFs) for filaments and film MPs, correspondingly, with filament and film being the most prevalent types of MP particles at the study site …

The potential polymer toxicity of detected MPs (represented by H_i) was assessed using a previously reported method [26], where designated scores are assigned to chemical components in specific plastic types and was calculated using Equation (3).

$$H_i = \sum P_n \, X \, S_n \quad \text{>Equation 3}$$

H_i represents the polymer risk index, P_n represents the polymer type ratio and S_n represents assigned hazard score for the polymer [26].

The last index utilized was pollution risk index (PRI) as presented below:

$$PRI = \Sigma \, H_i \times MPPLI_{site} \quad \text{>Equation 4}$$

PRI_i represents the ecological hazard of polymers in relation to the polymer risk index (H_i).

2.7. Quality control

The prevalence of microplastics in our environment has necessitated the implementation of stringent quality control measures during field sampling and sample processing in the laboratory to prevent airborne and cross-contamination by MPs. For this study, the following quality measures were implemented.

1. Glass and metallic materials and instruments were predominantly used throughout the study. Where plastic items were necessary, blank samples were processed to account for potential MPs contamination from such materials.
2. All materials, equipment, and workbenches were thoroughly cleaned before usage. Glass and metal items were autoclaved and rinsed three times with MilliQ ultra-pure water, while workbenches and metallic instrument surfaces were wiped down with ethanol or isopropanol.
3. To prevent airborne contamination from MPs during laboratory procedures, doors and windows were kept closed during sample processing and MPs analysis.

Table 2
Risk categories of indices utilized for detected microplastics [25].

Risk Category	Low (I)	Moderate (II)	High (III)	Very high (IV)	Dangerous (V)
Contamination Factor (CF)	<1	1–3	3–6	>6	
Pollution Load Index (PLI)	<1	1–3	3–4	4–5	>5
Polymer Risk Index (H)	<10	10–100	101–1000	1000–10000	>10000
Pollution Risk Index (PRI)	<150	150–300	300–600	600–1200	>1200

4. To minimize the risk of MPs contamination from clothing, the same set of clothing was worn during both field sampling and laboratory processes, with a preference for 100% cotton lab coats being worn.
5. Ultra-pure MilliQ water was used for rinsing and preparing solutions (such as 10% KOH and hypersaline solution), with the solutions processed through the Buchner filtration setup system with a mesh of 10 μm pore sizes to minimize and eliminate MPs contamination.
6. Aluminium foil was used to cover sample processing jars and solution bottles to prevent airborne MPs contamination.
7. The accuracy of our method was evaluated through a method recovery step, with at least an 80% recovery rate of MPs from all sample types, with the lowest recorded recovery rate observed for filaments in sediment.
8. Blank samples and controls were utilized throughout the study to identify and eliminate any MPs contamination.

3. Results

3.1. Water and sediment samples

Water samples had a mean concentration of 0.37 (±0.06) MPs/L and sediment samples had a mean of 38 (±2) MPs/kg (Fig. 2a). Microplastic abundance (MPs/I) and concentration (MPs/g) in various feeding strategies sampled in Simon's Town Marina indicated that scavengers/predators had significantly higher MP ($H(2) = -12.091$, $p = 0.208$) abundance (4.47 ± 0.51 MPs/I), when based on MPs per organism (Fig. 2b). Based on weight, MPs in grazers were highest (1.45 ± 0.27 MP/g), but the concentration was not significantly higher than in scavengers/predators ($H(2) = -5.304$, $p = 0.586$) (Fig. 2c).

MP shape analysis indicated that filaments were the most dominant MP type in both sediment and water samples (87 % and 98 %, respectively) (Fig. 3). Fragments were only recorded in sediment samples (6.7 %) and there were no spheres recorded for both sample types. Microplastic particle colour varied more in sediment samples than in water samples. Black particles dominated water samples with 53 % compared to only 12 % in sediment samples. Green particles dominated sediment samples. Yellow particles respresented the least in both water and sediment samples. MP size (μm) varied in sediment and water samples. The most dominant MP size in sediment

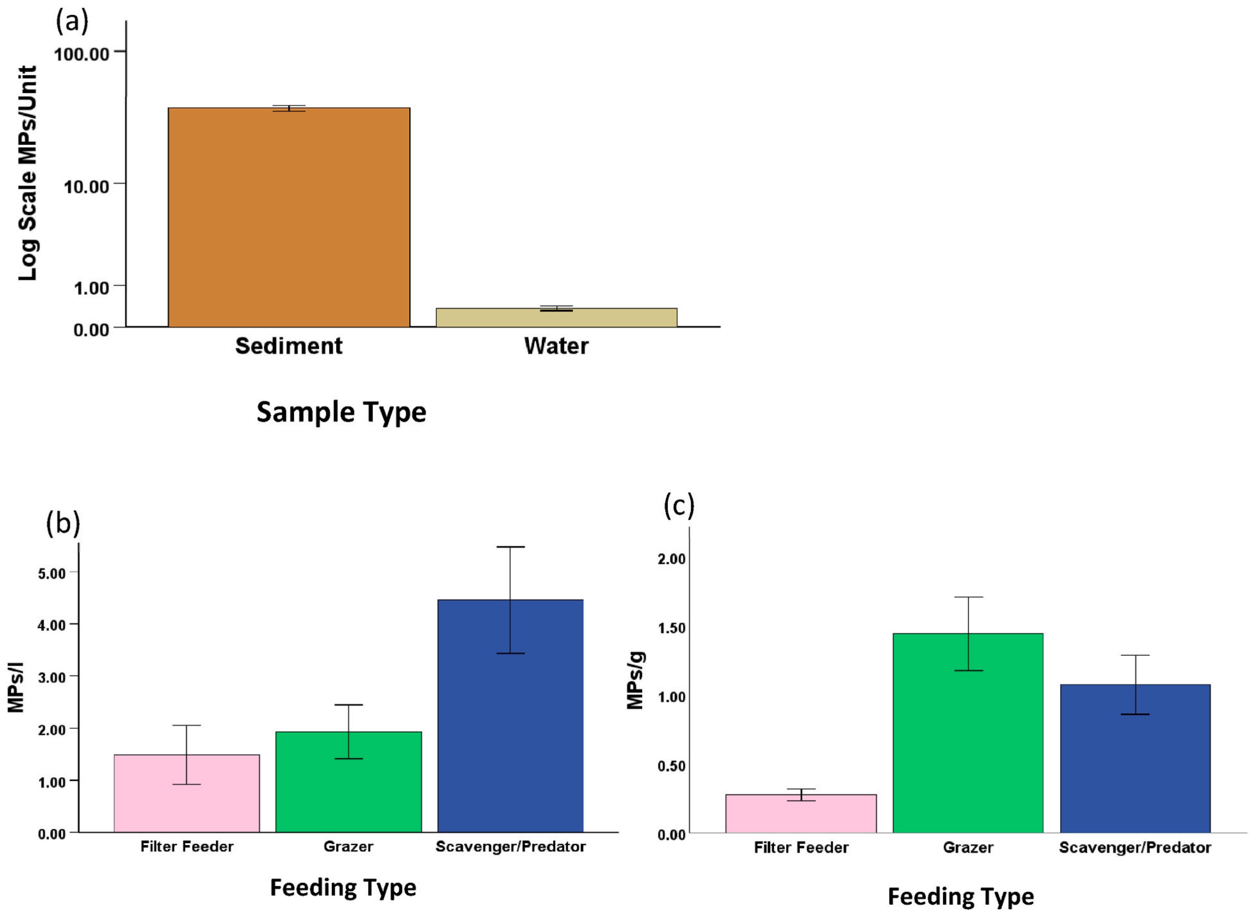

Fig. 2. (a) Mean MP concentration found in sediment (MPs/kg) and water (MPs/L) and (b) MP abundance (MPs/I) and (c) concentration (MPs/g) in various feeding strategies sampled from Simon's Town Marina.

and water samples was between 100 and 500 μm (75 % and 95 %, respectively) followed by MPs between 500 and 1000 μm (25 % and 5 %, respectively).

3.2. MPs in feeding types

MP type was analyzed and varied across various feeding types (Fig. 4). Filaments were the dominant MP type with grazers having the highest percentage (99 %). Fragments was highest in scavenger/predator samples (18 %). There were no spheres recorded in any biological samples. Black MPs dominated across grazers (60 %) and scavengers/predators (51 %). Green was the colour found mostly in filter feeders but is marginally higher than black MP particles. Filter feeders had a considerably higher percentage of transparent MP particles grazers and scavengers/predators.

MP size (μm) was analyzed in filter-feeder samples (Fig. 4). MPs between 100 and 500 μm was the most dominant size (83 %) followed by MP between 500 and 1000 μm (12 %) for all filter-feeder species combine. Redbait had the highest percentage of MPs between 100 and 500 μm (94 %) and mussels had the highest percentage of MPs between 500 – 1000 μm and 1000–2000 μm (17 % and 4 %, respectively).

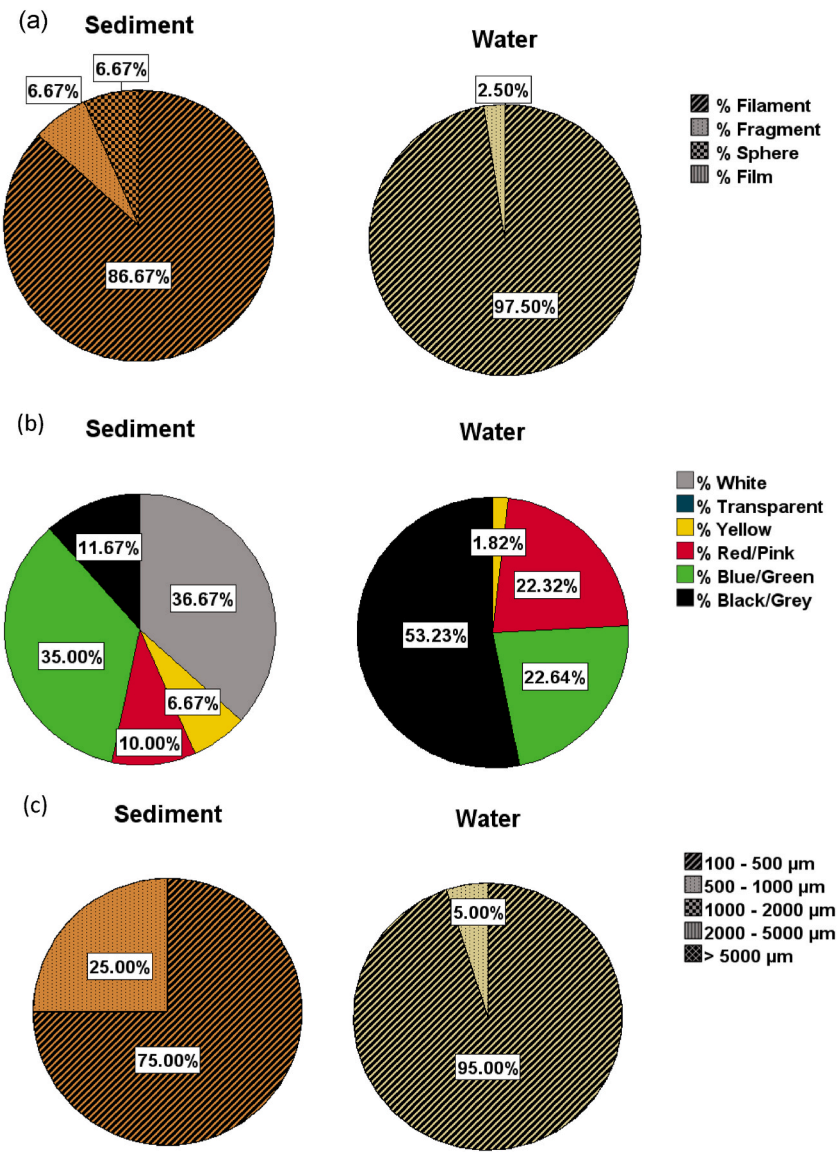

Fig. 3. The percentage of microplastics identified in sediment and water samples from Simon's Town Marina, categorized by MP type (a), colour (b) and size (c).

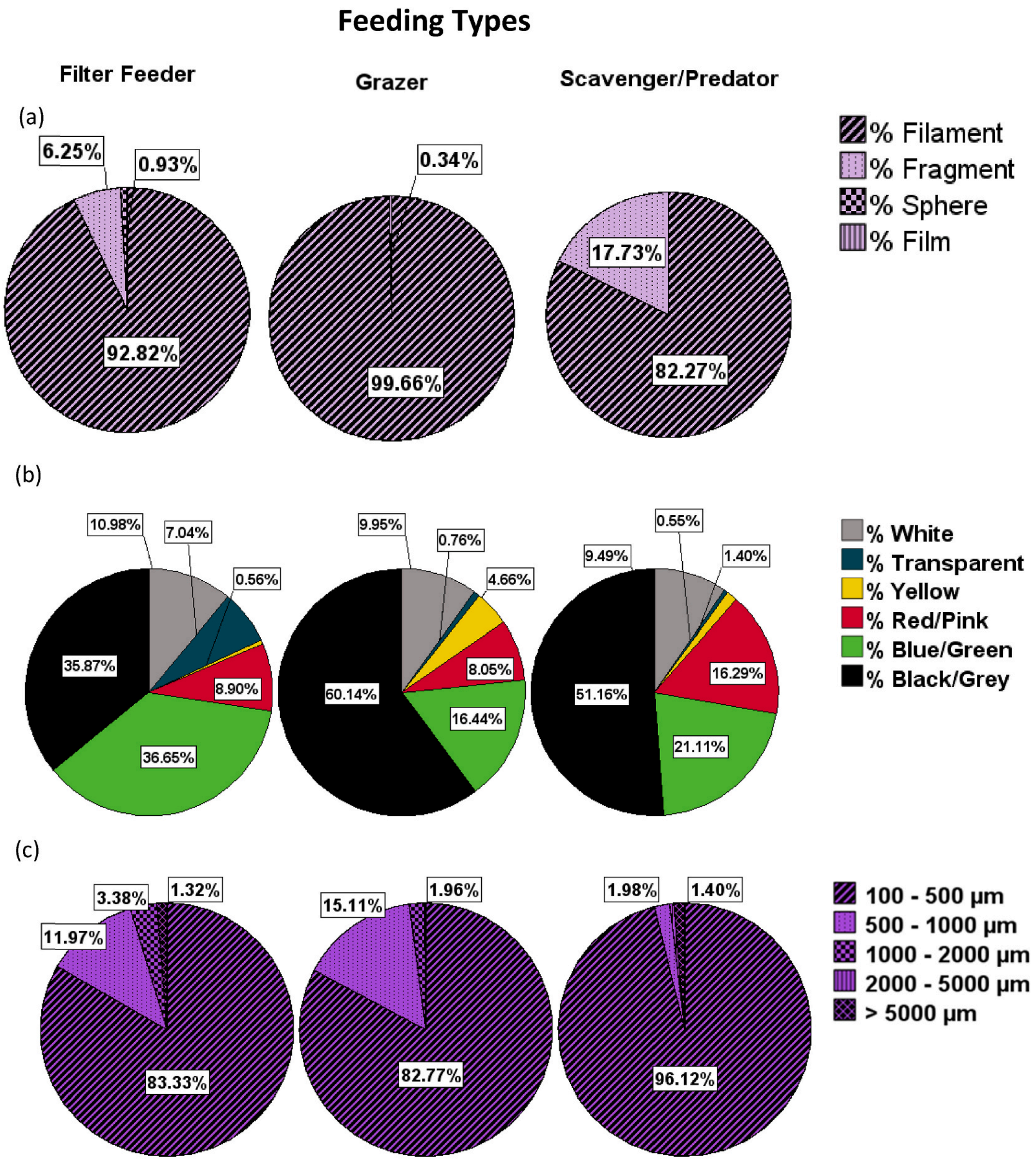

Fig. 4. The percentage of microplastics identified in various feeding types sampled from Simon's Town Marina, categorized by MP type (a), colour (b) and size (c).

3.3. Polymer identification using FTIR

Majority of the microplastics found within samples were nylon-based (PA6) polymers at 27 % of particles scanned by the FTIR (Fig. 5). The second highest was polyethylene terephthalate (PET) with 18 % recorded. Natural (NAT) particles were also recorded and was found to be cotton were also recorded at 18 % of samples. The lowest number of samples recorded was polyurethane (PUR) at 4.5 %.

3.4. Ecological risk assessment

The average Pollution Load Index (PLI) for all sample types combined showed dangerous (V) contamination levels (Fig. 6). Sediment, grazers and scavenger/predator samples displayed dangerous levels of MP contamination, whereas water samples and filter-feeding organisms was had as low and very high levels, respectively. The average Polymer Risk Index (H) showed a high risk associated with polymers identified in Simon's Town. Sediment and scavenger/predators had no risk associated with polymers identified. Water and grazer species displayed moderate and high risks associated with polymers identified, respectively. Filter-feeding species showed a

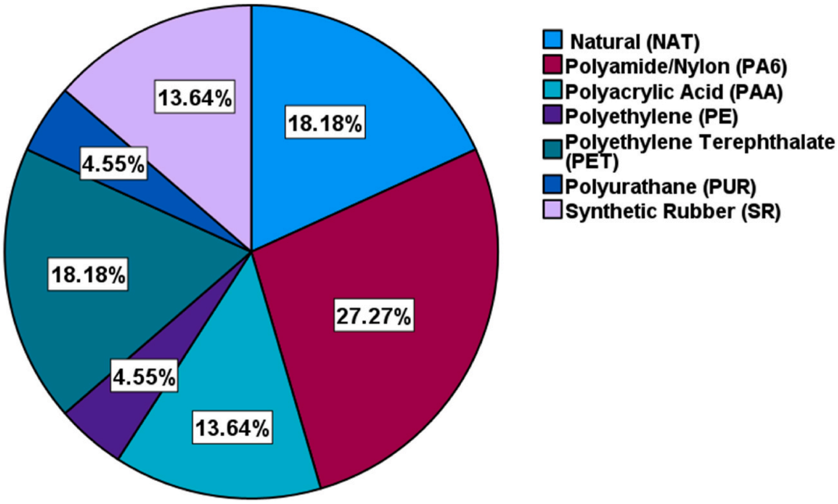

Fig. 5. Percentage polymer types found in microplastics samples in Simon's Town Marina.

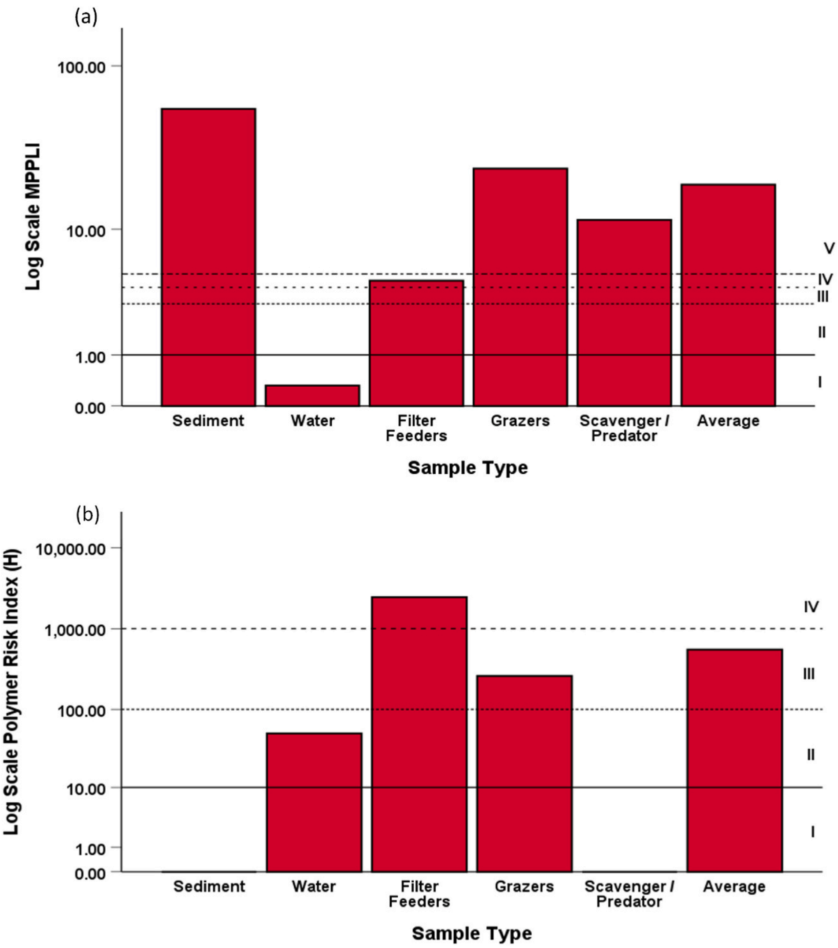

Fig. 6. Pollution Load Index [MPPLI] (a) and Polymer Risk Index [H] (b) between sediment, water, and the various feeding strategies from Simon's Town Marina.

very high risk associated with polymers identified.

The average Pollution Risk Index (PRI) for all samples combined showed a dangerous risk associated with pollutants identified in Simon's Town (Fig. 7). Sediment and scavenger/predator species showed no risk posed by pollutants. Water samples displayed a low risk associated with pollutants, whereas filter-feeders and grazers had a dangerous risk associated with pollutants identified.

4. Discussion

4.1. MPs in water and sediment

Since Simon's Town Marina sits within the greater Simon's Town Bay within False Bay itself, the water in and around Simon's Town Marina is very calm and the water retention in the area is very high [20]. Marinas are also built for the storage and protection of boats from rough seas and conditions, further making the waters in and surrounding marina's very calm and with low energy and wave action. This low energy environment allows heavier MP particles, such as fragments, to sink to the bottom of the water column. This is why there are more fragments in sediment samples than in water samples. The environment is calm enough to allow the lighter particles to settle in the sediment as well, as concentrations of fibres and film is nearly identical in water and sediment samples.

The average MP concentration in water (0.37 $\pm$ 0.06 MP/L) (Fig. 2) is similar to concentrations observed in water samples from Durban Harbour (0.41 MP/L) and Richards Bay Harbour (1.2 MP/L) in 2017 [27]. However, the average MP concentration recorded in water for this study is higher than the 0.15 $\pm$ 0.01 MP/L recorded in our other study that focused on MPs in coastal zones [28]. The mean MP concentration in sediment was 38 ($\pm$2.00) MPs/kg (Fig. 2). Many harbours and marinas are sites for boating maintenance. It was reported by Ref. [24] that at the same site of our research, which is opposite the boating maintenance facility in Simon's Town Marina, the fragments found in samples were mostly antifouling paint particles (APPs). MP sizes reported was less than 1 mm in size [29], which was similar for our study. A higher percentage of larger MP particles was found in the sediment than in water samples, further adding to the speculation of the low-energy environments allowing heavier MP particles to sink and accumulate in sediment (Fig. 2). Harbours tend to be MP sinks due the industrial nature of operations. This, added to the way marinas are built in order to provide shelter to vessels creating calmer, high-retention areas or water, can naturally increase the concentrations of MPs that are found in harbours and marina's [21]. The MP particles floating within the water column can be deposited along the sediment of the shoreline and is a representative sample of MP contaminants in the sediment [24]. Marine sediments play a vital role in the proper functioning of the marine ecosystem which include nutrient recycling, habitat for wide range of organisms, carbon storage, sediment transport and biostabilization, and water filtration, amongst others [30,31]. Notably, the interaction of sedimentary MPs with marine biota, can adversely affect their ecological functions, with dire consequences for the entire ecosystems [30,31]. Additionally, the uptake of sedimentary MPs by marine organisms may result in physical, chemical, and biological harm to these organisms. When these MPs contaminated organisms are consumed by humans, it could have dire consequences on human well-being [32]. In that, aside the intrinsic chemical makeup of MPs, MPs could also serve as vector for other harmful chemicals like heavy metals [33] and PAHs [34].

4.2. Microplastic classification

The type of MPs found in environmental samples (water and sediment) of Simon's Town Marina were that of filaments, fragments, and film (Fig. 3). The most abundant type of MPs found were filaments, with potentially heavier fragments found in the sediment as well. Film was also found in water samples. The fragments found were mostly APPs, which is likely from the boat maintenance facility in close proximity to the sampling site [24]. also found blue/green and red/pink fibres and fragments dominating sediment samples, in addition to black/grey fragments. This is very similar results found in this study, with black/grey, blue/green and red/pink fibres and

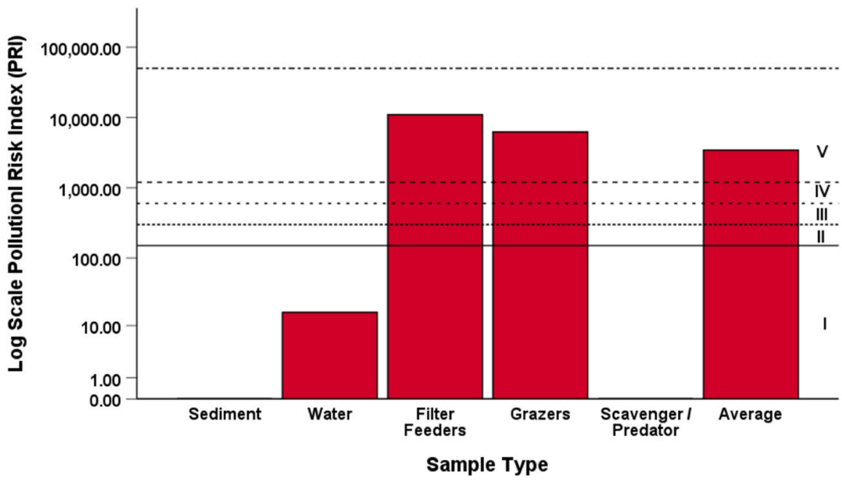

Fig. 7. Pollution Risk Index (PRI) a between sediment, water, and the various feeding strategies from Simon's Town Marina.

fragments found. Due to the boat maintenance facilities as well as many recreational activities occurring in the sheltered bay such as recreational boating, bathing, fishing and diving and many restaurants in the area, as well as a stormwater pipe [17], one can expect a variety of MP colours to be found. The size of MPs varied in water and sediment samples. This is due to environmental conditions (water circulation, photodegradation, bioturbation, wave and current action, wind etc.) facilitating in the production of MPs. The most dominant MP size in water and sediment was 1000 μm (1 mm) and smaller) (Fig. 3).

4.3. MPs in biota

4.3.1. Filter feeders

The main types of MP particles found worldwide is that of filaments [8], indicating that filaments are most likely to be taken up by any marine organism [29]. found the highest concentrations of MPs per individual at Simon's Town of all sites sampled [29]. also found that the most common type of MP found in Simon's Town was that of fragments, which was reportedly mostly APPs due to boating maintenance and repairs. The most common colours of MPs found were that of black/grey and blue/green, which is very similar results found in the area.

The sampling sites of this study was near a boating repair and maintenance site, which could be a contributing factor to higher concentrations of MPs recorded. With the site being a semi-enclosed marina, the water within the marina is retained for a longer period, being exposed to buoyant MPs for a longer period of time. The boat maintenance facilities in Simon's Town Marina does contribute to higher concentrations of APPs. Paint particles that are able to sink due to the heavier particle and calm waters settle in the sediments and pose health risks to the benthic environment [24].

MPs were recorded in all redbait samples collected off the east coast of South Africa [35]. More MPs was found in *P. stolonifera* in summer than in winter, with 138 particles found in summer across 30 samples compared to 107 particles found in winter [35]. Comparatively, MPs was only found in 45 % of redbait samples in this study. In summer [35], found that filaments were the most dominant MP type, which is similar to our study. It was expected that filter feeders ingested the highest variability of MPs due to their non-selective method of feeding [36]. Non-selective invertebrates such as filter feeders generally ingest more MP particles than organisms that utilise other feeding strategies to obtain food [29,35].

No significant differences in MP concentrations were recorded between filter feeders and water samples, which was expected. This could have been as result of the low-energy environment in the area sampled, resulting in MPs settling faster and making the MPs biologically available for a shorter period. With MPs settling faster than expected, they become part of the benthic zone and the sediment, exposing the organisms inhabiting the lower water column to MPs. This could explain the higher MPs recorded in grazers and scavengers/predators.

4.3.2. Grazers

Grazers feed by scraping food from hard substrates within the rocky shore. According to Ref. [9], grazers generally have a selective feeding pattern with ingesting food, which can include most algae found growing on rocks within the rocky shore. While *O. tigrana* had the lowest MP concentrations within the soft tissue (0.044 MP/g) amongst grazers for this study, *S. longicosta* and *P. exigua* are arguably more sessile than the periwinkle, which could contribute to higher concentrations of MPs in their soft tissue.

Although grazers are more selective than filter feeders, they are forced to feed in a more localised area, since they do not rely on suspended particles that float around the water column like filter feeders do. Rather, grazers settle in an area and feed on algae. If there it is an area of high MP contamination, grazers are forced to ingest whatever particles found that area, which could contribute to higher concentrations of MPs within the soft tissue. In Thailand, *Littoraria* spp. was found to have between on average 0.17 MP/g and 0.23 MP/g per organism between three sites [9]. This, compared to Ref. [37], *Littorina littorea* had on average 20 MP/g. Majority of the MP particles was that between the sizes of 300 μm and 5 mm in size [37]. The variation of data was deduced to be due to the variation of pollution in rocky shores and the relative distances to anthropogenic sources of MP pollution, which could be recreational activities and the boat maintenance repair in close proximity to the sampling site [9,38], which is similar to Ref. [29] and in this study.

[39] also found that majority of MPs found in *L. littorea* were that of filaments (97 %), with the highest site having on average 2.96 MP/g. This, compared to Ref. [37], is a lot lower than the 20 MP/g found in the Dutch environment. But higher, compared to the 0.044 MP/g in this study and 2.14 MP/g in Ireland [39].

In this study, we recorded 0.113 (±0.020) MPs/g in *S. longicosta* in the Simon's Town Marina [40]. reported on MPs in limpets (*Nacella magellanica*) from Argentina with the highest MP count per individual at 10.00 ± 6.69 MP/I from a site closest to many anthropogenic activities such as a harbour, and industrial area and fish processing factories. In their study, filaments ranged between 1.60 MP/I (±1.26 MP/I) and 5.70 MP/I (±2.36 MP/I) between three sites [40]. As with this study, filaments were also the most abundant type of MP found, contributing between 55 % and 61 % of total particles, followed by fragments which contributed between 29 % and 41 % of particles and films contributing between 3.4 % and 11 % [40]. Simon's Town Marina is also home to boating and other industrialised activities, as well as fish processing activities such as Ushuaia Bay in Ref. [40]. Blue, black and grey MPs dominated the site as well.

4.3.3. Scavengers/predators

Whelks were collected as scavengers within the rocky shore as it is known that they feed on dead and decaying matter within the rocky shore. In scavengers/predators, majority of the MPs were that of filaments (82 %). A similar study conducted by Ref. [41] found that majority of the particles found in three different snail species from three different sites had majority fragments found (52 %) with filaments the second highest MP shape (40 %). The blue and black colours also dominated [41]. MP concentrations in Ref. [41] was on average 3.19 (±1.67) MP/g which is slightly higher than this study of 1.84 (±0.33) MP/g.

The starfish, *M. glacialis*, had lower MP concentrations per gram than whelks of just 0.15 MP/g (±0.02 MP/g), but had a much larger MP count per individual organism of 6.680 MP/I (±0.854 MP/I). Scavengers and predators do not directly take up MPs from the sediment or water, but studies suggest that they feed on organisms or detritus that is already contaminated with MPs. This gives potential for MPs not only to be passed on through various trophic levels, but to bioaccumulate and biomagnify [42,43].

4.4. Polymer identification

10 % of identified MPs was processed for FTIR analysis and identified polyamide-nylon (PA6) as the dominant polymer type (27 %) followed by natural based polymer and PET (18 % and 18 %, respectively) (Fig. 5). These results are reflective of what was found in a study conducted by Ref. [24]. Polyamide/nylon (PA6) is used to produce fishing nets. This could explain for the high percentage found within the marina. Applications of PET include plastic bottles which are prone to ultra-violet degradation [44]. This makes PET based products prone to forming secondary MPs. In addition, PET has a higher density than other polymer types and with the facilitating weak circulation [21,24] within the marina increases this polymer type's settling rate. Thus, also making these polymers susceptible to being ingested (directly or indirectly) by organisms residing and feeding from benthic environments. Applications of natural based products include clothes and ropes used on boats, could explain the high percentage of natural particles. These applications in combination with marina related activities and pedestrian access could potentially be linked to sources for MP contamination. The remaining polymers identified could be linked to other applications, sources and environmental conditions within Simon's Town and False Bay.

4.5. Risk assessment of microplastics and polymers

The Pollution Load Index (PLI) showed generally high to dangerous levels of MP pollution within Simon's Town (Fig. 6) particularly in sediment and all biological samples. Whereas water samples displayed low levels. This is concerning for species residing and feeding in benthic areas as they could potentially be consuming (directly or indirectly) MPs that have accumulated in sediment. The dangerous levels observed in sediment reinforces sediment as a MP sink. MPs that have settled in sediment can be resuspended in the water column, making these MPs available to be consumed by organisms feeding from the water, particularly filter-feeders. MPs are mistakenly identified as food particles and are consumed by various organisms depending on feeding strategy. This could explain why filter-feeding species displayed a very high-risk levels (Figs. 6 and 7) as they have a non-selective feeding strategy ingesting particles of various type, colour, and size. The Polymer Risk Index (H) (Fig. 6) showed generally a high risk associated with polymers identified in Simon's Town. It is important to note that even though filter-feeding species did not display the highest mean MP concentration, it had a noticeably very high risk associated with polymers. This indicates that the risk is not dependent on concentration, but the polymers identified and their hazard score. Poly Urethane (PUR) had a hazard score of 13844 [26] and was only identified in filter-feeding species. Polymers with high assigned hazard scores have the potential to pose a threat to organisms ingesting the particle. The Pollution Risk Index (PRI) is dependent on the PLI and H calculated. For this study, levels showed a dangerous risk associated with pollutants, particularly in filter-feeder and grazer species (Fig. 7). This is concerning as filter-feeders are non-selective in their feeding strategy and grazers have the potential to indirectly consume pollutants by scrapping contaminated algae off rocks.

5. Conclusions

The result of this study suggests that MPs concentration and abundance is heavily linked to anthropogenic activities. The area surrounding Simon's Town Marina has restaurants and other recreational activities, commercial fishing, and boating activities as well as boat maintenance and boat building activities. These factors could influence MP types, sizes and colours found within the environment. The prevalence of MPs at our site, stresses the need for sterner enforcement of existing laws on the use and disposal of plastics in the marine environments, with the introduction of new laws to specifically minimize the release of MPs into Marinas.

The MP type, size and density are main factors that determine where within the water column the MPs are found. Heavier MPs, such as fragments, are generally known to settle into the sediment quicker than lighter MP particles, such as filaments. Filaments are therefore more commonly found in organisms with non-selective feeding strategies, such as filter feeders, whereas fragments are more commonly found in organisms that appear in the benthic region of the water column, such as grazers.

Majority of the MP particles isolated from organisms were dark in colour, indicating that organisms are mistaking darker MP particles for food when feeding. Scavenging and predatory organisms are unlikely to take up MP particles directly from the water column, and it is thought that MPs found within scavenging and predatory organisms provide evidence for MP particle transfer through various trophic levels and could lead to bioaccumulation and biomagnification, although more research should be done to confirm this.

With Simon's Town Marina being an environment of low water energy, MPs are more susceptible to sinking and settling in the sediment, as the sediment is thought to be a microplastic sink. The most common MP polymer types were found to be nylon (27 %), natural MP such as cotton filaments (18 %), PET (18 %), synthetic rubber particles in the form of antifouling paint particles (14 %) and acrylic particles (14 %). These are all forms of plastics expected from recreational activities, but also expected from the boat maintenance and building facility that is within close proximity to the sampling site. A risk assessment was also conducted, and it was found that the high risks that MP particles pose is due to the MP polymer type and not MP concentrations. Hence, the government needs to do more to educate the residents, tourists, and businesses in areas like Simon's Town Marina about MPs pollution and their potential impacts on the marine ecosystems. The awareness should emphasize the reduction of plastics usage, especially single-use plastics, proper waste disposal and management, and the adoption of sustainable practices.

It is recommended that seasonal sampling is undertaken for MPs to gain more knowledge and understanding, as well as to form a historical record of MP pollution in the area. These studies serve as a baseline study for future research and proves that further research is required to understand the full extent of MP pollution in the area, and in rocky shores in South Africa. It is also recommended that more experimental studies are done to reinforce the findings and for more acute-exposure studies, the focus of research should be done on hours one to three after initial exposure. This study displays the need for more research to be done on the topic and can add to historical data on the topic. The combination of field and experimental studies a more wholistic approach and understanding to microplastic pollution. Thus, it is imperative for government to allocate resources to MPs monitoring and experimental studies aimed at better understanding the sources, exposure pathways, fate, and effects of MPs in marinas.

CRediT authorship contribution statement

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

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.

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