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Microplastic pollution in Marine Protected Areas of Southern Sri Lanka

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ABSTRACT

Microplastics (MPs) are ubiquitous in marine environment. The prevalence of MPs in coastal and lagoon sediments, and water were studied in two Marine Protected Areas (MPAs); Bundala National Park (BNP) and Hikkaduwa Marine National Park (HNP) in Sri Lanka. Both areas are important for turtles, birds and coral ecosystems, all of which are particularly threatened by MPs. Abundance of MPs was generally higher in both coastal sediments and waters in HNP (111±29 MPs/m^2 for sediments and 0.515±0.054 MPs/m^3 for water) than in the BNP (102±16 MPs/m^2 for sediments and 0.276±0.077 MPs/m^3 for water). The most common shape and polymer type of MPs were fragments and Polyethylene respectively. This research is the first to survey MPs in MPAs in Sri Lanka and provides a baseline of MPs pollution in these environments for future research and management.

1. Introduction

Plastics have become indispensable in several sectors, due to some of their unique characteristics, which make them versatile, strong, durable, inexpensive, and lightweight (Andrady, 2011; Plastic Europe, 2017). To match the increasing worldwide demand, plastic production has increased rapidly. An estimated 19 to 23 million metric tons, or 11%, of plastic waste generated globally in 2016 entered aquatic ecosystems (Borrelle et al., 2020). At current rates of plastic production and waste generation, the annual mass of mismanaged waste is projected to more than double by 2050 (Geyer et al., 2017; Lau et al., 2020; Lebreton and Andrady, 2019).

Microplastics (MPs) are defined as plastic particles smaller than five millimeters (5 mm), they are omnipresent and contaminate the world's oceans. Two types of MPs have been found entering to the ocean via land based sources or ocean based sources, they are grouped based on whether they are intentionally manufactured to be of microscopic size (primary) or derived from fragmentation and degradation of larger plastics (secondary). Secondary microplastics are more abundant in the ocean and the estimation of secondary microplastics input is far more arduous (Andrady, 2017). Secondary microplastics can be formed as the result of the weathering and physical fragmentation of plastic beach litter (Andrady, 2017). The breakdown is promoted by high UV exposure and physical abrasion by waves, eventually weakening and embrittling the plastic until it degrades into smaller fragments (Andrady, 2011; do Sul and Costa, 2014). Treated and untreated sewage discharges into rivers, coastlines, and the atmosphere are the major entry points of MPs into the oceans. Fisheries, Aquaculture, shipping and offshore industries are some of the major sea based sources for MPs, contributing to the plastic soup (GESAMP, 2016).

The negative consequences of MPs on ecology, economy, human health and food security are hot topics among scientists worldwide as indicated by their prevalence of literature (Nielsen et al., 2019). MPs cause serious negative impacts on important ecosystem species, including fish, sea turtles, corals and sea birds (ICC, 2016). Scientists predict that nearly 99% of all sea bird species and virtually 95% of all individual sea birds would have ingested plastics by 2050 (ICC, 2016). Not only sea birds, but also 100% of sea turtle species worldwide will ingest plastic (ICC, 2016). Due to their small size and availability, the ingestion of MPs by a wide range of marine organisms (planktons to whales) has been observed (Gall and Thompson, 2015). The leaching of additives from plastics and the sorbtion and concentration of toxic

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pollutants (also called Persistent Organic Pollutants or POPs) from surrounding sea water can all play an effect once MPs are ingested. MPs can also act as vectors to transport pathogens and invasive species (Avio et al., 2017; Silva et al., 2019; Zettler et al., 2013). The ingestion of MPs and long term exposure can lead to sublethal (Auta et al., 2017; ICC, 2016) or lethal effects (Maes et al., 2020) across a wide range of animals.

The composite life history and high mobility of marine turtles increases the possibility of impact by MPs pollution via direct or indirect interactions. These include, the heat retention of MPs in the beach which influences the hatchling sex ratio and reproductive success of nests and chronic effects related to the exposure to MPs via the consumption of sea weeds, molluscs and small fish (Beckwith and Fuentes, 2018; Cammilleri et al., 2017; Wright et al., 2013). Seabirds are prone to ingest MPs, the migratory habits of seabirds even affect the global distribution of macro and microplastics through bio-transportation (Kühn et al., 2015). There are various consequences of MPs ingestion by seabirds: reduced food intake; decreased efficiency of the digestive process; formation of ulcers in the digestive tract; other sub lethal and lethal effects (Kühn et al., 2015). Most of the plastic waste is accumulated in tropical regions, near the equator rather than in polar regions, so there could be higher risk of plastic contamination to coral reefs (Lamb et al., 2018). Lamb et al. (2018) has reported that the presence of plastics increases coral disease outbreaks, from 4% to 89%. So coral reefs and associated flora and fauna can be severely affected by MPs pollution. Hall et al. (2015) also shows various negative effects on the health of corals resulting from the ingestion of MPs.

A Marine Protected Area (MPA) is defined as being any area of intertidal or subtidal terrain, together with its overlying water and associated flora, fauna, historical and cultural features, which has been reserved by law or other effective means to protect part or all of the enclosed environment (Dudley, 2008). MPAs are one of the most popular ways for the management of the marine resources. Regardless of protection strategies of MPAs, most of the MPAs in the world are highly exposed to the plastic pollution (Barnes et al., 2018; Lavers and Bond, 2017). Irrespective of the conservation efforts, Anthropogenic Marine Litter that has arrived to the coasts of MPAs can permanently threaten the biodiversity of MPAs (Luna-Jorquera et al., 2019).

Tourism, fishing and most of the other industries in Sri Lanka are located and associated with the coastal zone and therefore, pressures on the coastal resources are high. Staub and Hatziolos (2004) have developed a scorecard approach to determine the management status of MPAs. According to that, Sri Lanka's MPAs management status was regarded as poor, and various human activities and degradation of natural resources happen continuously (Perera and De Vos, 2007). In Sri Lanka, about half of the MPAs are located within the Southern coast emphasizing its ecological value. In this study, two MPAs on the Southern coast were selected, Bundala National Park (BNP) and Hikkaduwa Marine National Park (HNP). These locations were selected because of their prominent marine conservation species (corals, sea turtles, and migratory birds) and the degree of anthropogenic activities in these areas. BNP is an internationally important wintering area for migratory sea birds and the adjacent coastal area supplies nesting grounds for all five species of sea turtles. Hikkaduwa reef provides a habitat for a wide range of marine flora and fauna including "Near-Threatened", "Vulnerable", "Endangered" and "Critically Endangered" marine organisms.

Despite the increased awareness, accumulation of MPs in MPAs and its impacts on marine biota in Sri Lanka has not received any attention. A few studies have investigated MPs in MPAs in Spain, Croatia, Scotland, the Atlantic, the Mediterranean and the South Pacific (Barnes et al., 2018; Bayo et al., 2019; Baztan et al., 2014; Blašković et al., 2017; Fossi et al., 2017; La Beur et al., 2019; Luna-Jorquera et al., 2019; Masiá et al., 2019; Panti et al., 2015; Ronda et al., 2019). This research is aimed at generating MPs baseline data to investigate the extent of contamination, and guide further research on the ecological impact of MPs contamination. Such studies are urgently needed and important to design and implement new plastic legislation protecting wildlife in MPAs.

2. Materials and methods

2.1. Geographic context and study sites

Bundala National Park (BNP) and Hikkaduwa Marine National Park (HNP) were the two main sites that were selected for this study. Each of these two sites was further divided into sub sites (12 in total) to gather quantitative and compositional data on MPs.

Bundala National Park (BNP) is located in Hambantota district. It covers a total area of 6216 ha of lowland with 20.97 km coastline (van der Hoek, 1998). Bundala is the Sri Lanka's first Ramsar wetland. BNP harbours a rich bird life including migratory birds, seabirds and resident birds. At one time, BNP accommodates over 15,000 shore birds. Around 197 different bird species were identified in BNP, including 58 species of migratory birds. The park also shows rich biodiversity, including 32 species of mammals, 48 species of reptiles, and 32 species of fish (Perera, 2007). Globally, there are seven species of sea turtles, and Sri Lanka hosts five species, which are listed on the IUCN Red List either as "Endangered" or as "Vulnerable". Bundala is one of the Sri Lankan beaches (out of 5) on which all five turtle species nest (Jayathilaka et al., 2017). According to the Amarasooriya (2000) classification, Bundala beach is ranked as a high value "class 2" beach, based on the presence of all five species of marine turtles, with an average of five or more nests per month. Those five species are *Chelonia mydas*, *Caretta caretta*, *Dermochelys coriacea*, *Eretomchelys imbricate* and *Lepidochelys olivacea* (Joseph, 2003).

In BNP, seven sub sites were selected along the coastline, based on the presence of turtle nesting areas, fisheries activities and lagoon mouths. Those were named from B1 to B7. The B1 and B5 site are within small fishing harbours, Uraniya and Pathiraja respectively. The B2, B4 and B6 site are prominent turtle nesting areas. The B3 site is the Bundala lagoon mouth and the B6 site is near to the Malala lagoon mouth. Malala Modhara is the local name for the B6 site. Here, the lagoon connects with the ocean via a man-made canal. It is also one of the major turtle nesting site within this MPA. Coastal surface water samples were taken in three locations: at the W1, W2, and W3 site within the park boundaries. In BNP, there are three major lagoons: Bundala, Malala and Embilikala. These are residential, breeding and feeding grounds for migratory birds. Therefore, sediment and water samples from these lagoons were analyzed to determine abundance of MPs (Fig. 1).

Hikkaduwa Marine National Park (HNP) is located in the Galle district. HNP covers 104 ha of surface area. The habitat of HNP is mostly composed of coral reefs. HNP was the first true Marine Protected Area of Sri Lanka. Hikkaduwa reef provides a habitat for a wide range of marine flora and fauna, including "Near Threatened", "Vulnerable", "Endangered" and "Critically Endangered" marine organisms. There are 60–70 species of shallow water corals identified in HNP with 170 species of marine or "saltwater" fish species. Also, seagrass beds are present inside the national park, providing habitat, food and also nursery grounds for numerous types of marine fauna (Wilson, 2018).

In HNP, five sub sites were selected along the coastline: the H1 to H5 sites. The H1 site was located near Hikkaduwa fishery harbour. The H5 site was located on the other side of the national park near to a large hotel. The H2 site is near a boat anchoring area, where several dive boats and glass bottom boats are anchored. The H3 site is located near a large drainage outlet from Hikkaduwa town and other neighboring areas. The H4 site is near to a seagrass bed. At the H4 site, there is a narrow beach due to hotel construction, therefore coastal sand samples were collected only at the high tide line. There are large hotels, guesthouses and other small constructions along the entire coastline. Coastal surface water samples were taken in two locations: at the HW1 and HW2 site within the park boundaries (Fig. 2).

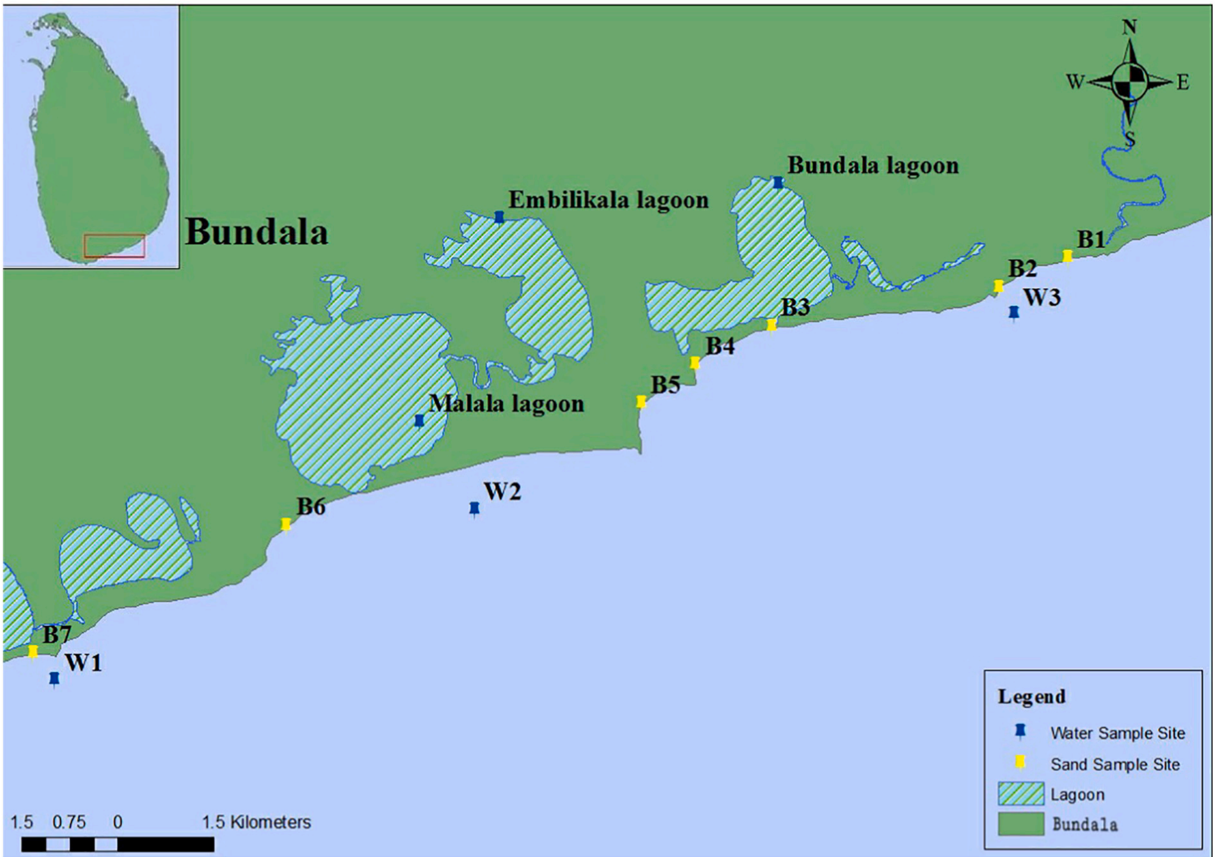

Fig. 1. Sampling location of Bundala National Park (BNP).

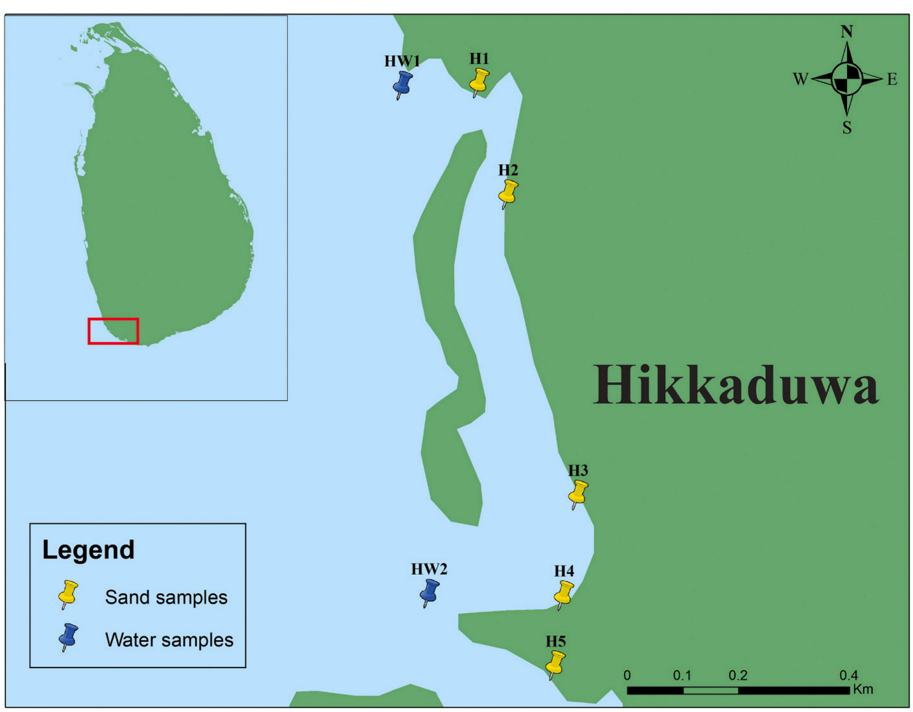

Fig. 2. Sampling location of Hikkaduwa Marine National Park (HNP).

2.2. Overview of sampling

Coastal sand samples were collected in October 2018. For each sub site (in BNP 7 sub sites and in HNP 5 sub sites) two 100 m transects were placed along the high tide line and dune/vegetation line parallel to the shoreline. GPS coordinates were recorded at each sub site. Using a random number generator, four random numbers were generated between 0 and 100 for each sub site. According to the Marine Strategy Framework Directive (MSFD) guideline, quadrats were placed at least 5 m apart from each other. So, additional random numbers were generated if two of the random positions were closer than 5 m. Then four 50 cm × 50 cm quadrats were positioned randomly along each transect. At each quadrat, big pieces of natural debris were removed and the top layer of sand was collected,2 cm depth evenly, using a stainless metal shovel (Calcutt et al., 2018; Losh, 2015). Altogether, there were 96 sand samples.

To collect coastal water samples, an 80 μm mesh size plankton net (50 cm diameter) was deployed from the side of the boat and GPS coordinates and start time were recorded. The boat moved in a straight line parallel to the shoreline (100 m – 200 m from the coastline) at a speed of 2–3 knots for 15 min. After 15 min, the net was lifted from the water and the final GPS coordinates were recorded. The net was rinsed thoroughly with sea water from the outside, from the mouth to the cod end to concentrate all particles in the cod end. The cod end was removed and the sample was transferred to labelled glass bottles until further analysis. The cod end was rinsed one last time, from the outside, to wash off adhered particles (Kovač Viršek et al., 2016). Traditional canoes were used to collect water samples in the lagoons. To collect water samples in the lagoons, the plankton net was towed in the center of the lagoon for a distance of 50–100 m. Benthic sediment samples of the three lagoons were collected with an Ekman Grab at the start locations of the water sample transects.

The sampling distance was found by using the initial and final GPS coordinates. To calculate the sampling volume, $r^2 \times L$ general formula was used, where = 3.1415, r = radius of net opening (in m) and L = distance net was towed (in m). Then number of collected MPs were divided by the sampling volume. The abundance of MPs in water was expressed as the number of MPs per cubic meter (Number of MPs/m^3).

2.3. Separation of MPs and laboratory analysis of samples

Sediment samples were sieved with the aid of a sieve set using 2 mm, 1 mm and 500 μm mesh size sieves (Retsch GmbH, AS 200 (operated under 40 rpm for 10 min)).The remaining sediment on each sieve was transferred to vials and topped up with 1.2 g cm^{-3} NaCl solution for density separation via centrifugation. The larger floating MPs were manually removed from the surface and placed on petri dishes. The supernatant was filtered through GF/C filter paper using a Buchner funnel. The MPs on petri dishes and filter papers were placed under a stereomicroscope (LEICA MZ6) for observation (×40). The number of MPs, type and color were recorded. MPs between 1.1 and 5 mm were measured using a digital Vernier caliper and weighed with an analytical balance.

A blank was performed following the same steps as the analyzed samples. To avoid airborne contamination, throughout the process of MPs separation and analysis, samples, solutions and water were covered and all the materials were triple rinsed with deionized water (Courtene-Jones et al., 2017).

MPs were categorized according to their size, shape and color (Maes et al., 2017b). We introduced two main size ranges: between 5 mm – 1.1 mm and 1 mm – 0.5 mm and defined those as "large MPs" and "small MPs" respectively. According to their shape, MPs were divided into five categories: fragments (hard angular pieces of plastic), filaments (single or multiple twisted/woven fibers), films (thin, flexible pieces of plastics, mostly transparent in color), foams (usually white and spongy) and pellets (distinctive cylindrical, disc or lentil like shape). Main color categories were found as white, blue, green, red and others.

To identify the polymer type and oxidation level of selected "large MPs", a spectroscopic analysis was done. For this, randomly selected 50% of the large MPs from each site were analyzed using FTIR (Thermo Scientific Nicolet S10 FT-IR spectrometer). A portion of those particles were also analyzed with Raman spectroscopy (LabRAM HR800 spectrometer) for further confirmation. To identify oxidation, an indication of the "age" of the MPs, the height of the 1715–1775 cm^{-1} peak of FTIR spectra was identified, representing the C = O bond and oxidation level.

To identify "small MPs" on filter papers, freshly prepared Nile red solution was used (Maes et al., 2017a). The MPs in these samples were first counted visually, assuming particles to be plastic, depending on appearance. Then Nile red was added to filter papers, using a droplet which was allowed to stain MPs for about 5–10 min. The filter was then examined under a stereomicroscope (×40) using a UV flashlight to recount the stained particles (Andrady, 2011; Fowler et al., 1987; Shim et al., 2016).

2.4. Statistical analysis

Microsoft Excel 2016 and IBM SPSS Statistics software (version 25) were used for statistical analysis. One way ANOVA and Pearson correlation were carried out using SPSS software.

3. Results and discussion

3.1. Abundance and distribution of microplastics

In BNP, MPs were observed in coastal sands at all seven sites in both high tide lines and dunes. A statistical significant difference was found among mean abundance of total MPs at the high tide line ($p = 0.009$). The mean abundance of total MPs counts for the high tide line ranged between a maximum of 187 ± 10 MPs/m^2 at the B1 site and a minimum of 53 ± 1 MPs/m^2 at the B6 site (Fig. 3 and Table 1). The B1 site is located near the boundary of the national park. The Kirindhi Oya river mouth also was adjacent to this site. According to Karthik et al. (2018) adjacent to the river mouth, a high abundance of MPs were recorded in beach sediment. River mouths have been considered to be a major entry point of land based debris into the ocean (Carr et al., 2016; Jambeck, 2015; Kataoka et al., 2019; Lebreton et al., 2017). This high concentration of MPs in coastal sand at the B1 site could thus be the result of its position adjacent to the Kirindi Oya river mouth. Such high abundance of plastic, accumulating near river mouths, was also reported in several other studies (Chang et al., 2018; Santos et al., 2009). Furthermore, there could be an influence from the SouthWest Monsoon current, pushing MPs onto the B1 site. The minimum abundance of MPs at the high tide line was recorded at the B6 site. On the beach of the B6 site, the wave action was considerably higher compared to other sites within the MPA. MPs and other items may be constantly removed by strong wave action as a result (Harris, 2020). Although, Malala lagoon connects with the ocean at this location, there is little or no land-based debris entering the ocean through this canal.

The mean abundance of the total MPs count within dune sand, ranged between a maximum of 196 ± 13 MPs/m^2 at the B4 site and a minimum of 39 ± 3 MPs/m^2 at the B5 site. The dune area in BNP has a special importance because it forms prime turtle nesting grounds. Nevertheless, the highest abundance of MPs was recorded at the B4 site which is higher than the highest value recorded on the high tide line at the B1 site. In the B4 site, the coastal morphology of the beach forms an embayment with high amounts of macro plastics and mollusk shells. The high wave action on the high tide line constantly removes and re-deposits MPs (Harris, 2020). Over time, MPs get blown into the dunes, where they gradually accumulate. Interestingly, the lowest abundance of MPs was found in the dune areas at the B5 (Pathiraja) site. This site was selected due to its fishing activities. The results indicate that the fishing activities itself do not contribute to MPs pollution, contrary to what we observe in large fishing harbours.

There is a decreasing trend of total abundance of MPs by count (mean of total MPs at the high tide line and dune) from B1 to B7. Sampling was conducted on 2nd of October 2018. In this month the SouthWest Monsoon (June to October) generally operates and the currents flow

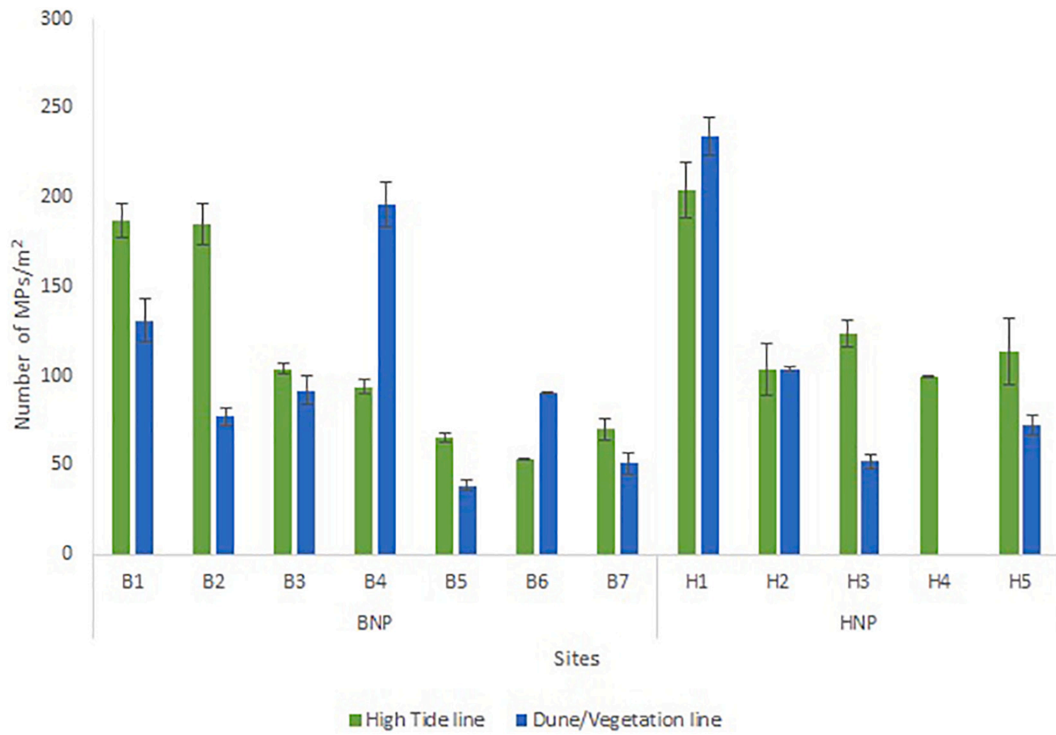

Fig. 3. Abundance of total MPs at each sites in high tide line and dune of Bundala National Park (BNP) and Hikkaduwa Marine National Park (HNP) in terms of Number of MPs/m^2 ± SE.

Table 1
Count and weight of MPs at high tide line and dune/vegetation line in Bundala National Park and Hikkaduwa Marine National Park (mean ± SE).

Site	High tide line			Dune/vegetation line		
	Number of MPs/m^2		g of MPs/m^2	Number of MPs/m^2		g of MPs/m^2
	Small MPs	Large MPs	Large MPs	Small MPs	Large MPs	Large MPs
Bundala National Park						
B1	111 ± 12	76 ± 4	1.31 ± 0.11	118 ±14	13 ± 2	0.26 ± 0.05
B2	63 ± 7	123 ± 12	2.32 ± 0.25	40 ± 3	37 ± 5	0.34 ± 0.06
B3	62 ± 8	42 ± 11	0.55 ± 0.14	60 ± 8	32 ± 8	1.39 ± 0.19
B4	94 ± 4	0	–	99 ± 6	97 ± 15	0.42 ± 0.11
B5	29 ± 2	36 ± 1	0.23 ± 0.02	24 ± 1	15 ± 2	0.06 ± 0.01
B6	36 ± 2	17 ± 1	0.15 ± 0.02	31 ± 3	60 ± 6	0.31 ± 0.02
B7	70 ± 6	0	0.00	51 ± 8	0	0
Hikkaduwa Marine National Park						
H1	59 ± 3	145 ± 12	3.94 ± 0.34	84 ± 7	150 ± 4	3.00 ± 0.26
H2	27 ± 5	77 ± 10	1.09 ± 0.24	45 ± 5	59 ± 5	0.31 ± 0.03
H3	51 ± 4	73 ± 11	0.51 ± 0.10	30 ± 2	22 ± 3	0.00
H4	21 ± 1	79 ± 1	0.73 ± 0.00	–	–	–
H5	36 ± 5	77 ± 4	1.41 ± 0.26	48 ± 5	24 ± 1	0.48 ± 0.08

from West to East during this season (Vos et al., 2014). This could be a reason for the increment in MPs from B7 to B1. Similarly, Chang et al. (2018) also observed the influence of the NorthEast Monsoon currents on debris accumulation along the East coast of Sri Lanka. The monsoon cycle and its relation to debris distribution and accumulation were also highlighted in several other studies; Jayasiri et al. (2013) describes the accumulation of marine based items, particularly fishing related items in Indian beaches during the monsoon season of India; Duhec et al. (2015) reported changes of accumulation of marine debris in Alphonse Island, Seychelles with SouthEast and NorthWest Monsoon.

In HNP, MPs were identified in coastal sands at each of the five sites on both high tide line and the vegetation line (Fig. 3 and Table 1). The difference among mean abundance of total MPs at high tide line sites was insignificant ($p = 0.627$). The mean abundance of total MPs at high tide line sites ranged between a maximum 204 ± 16 MPs/m^2 at the H1 site and a minimum of 100 ± 1 MPs/m^2 at the H4 site.

The H1 site shows the highest abundance of total MPs for both high tide (204 ± 16 MPs/m^2) and vegetation line sites (234 ± 11 MPs/m^2). The H1 site is located close to Hikkaduwa fishing harbour near the boundary of the national park. The pollution in HNP by this fishing harbour coincides with the presence of high percentages of polystyrene particles (30%) in both high tide line and dune coastal sand samples. In vegetation line sites there was a significant difference in total MP abundance among sites ($p = 0.006$). The number of total MPs ranged between 234 ± 11 MPs/m^2 (H1 site) and 52 ± 4 MPs/m^2 (H3 site).The H3 site is located near the outlet and we observed dark, polluted water draining into the ocean through this canal. Large amounts of natural and plastic debris accumulated on the nearby beaches. This waste is removed by nearby hotels to maintain the natural beauty despite the ongoing coastal erosion in this area.

When compared with BNP, HNP shows the highest abundance of MPs by count for both the high tide line (129±19 MPs/m^2 for HNP vs. 108±21 MPs/m^2 for BNP) and dune (116±37 MPs/m^2 for HNP vs. 97±20 MPs/m^2 for BNP). HNP is located near a fishing harbour, a populated urbanised city and a highly visited tourist beach. Several canals drain highly polluted water with MPs and other plastic debris into the national park. In contrast to HNP, the BNP sites were located at a remote beach located far from Hambanthota City and Hambanthota and Kirindha fishing harbours. Even though bird watching is popular within the national park, a permission to carry out any activities in the national park is needed from the Department of Wildlife Conservation (DWC) in Sri Lanka. While fishing activities are conducted in two places in BNP, pollution from those activities is very low. There may be some MPs input from the Kirindhi Oya near BNP. Compared to HNP, local sources of plastic and MPs are very low in BNP and the only major contributor of pollution into the national park is from ocean currents. This type of pollution, externally produced MPs, was also observed in 125 beaches of the Canary Islands with MPs arriving via the Canary Current (Baztan et al., 2014). Luna-Jorquera et al. (2019) also highlighted the pollution of South Pacific MPAs by distal sources of MPs.

Sandy beaches along exposed coasts are the most dynamic of all sedimentary environments, being continuously exposed to breaking waves and currents varying with tidal range (Harris, 2020). Next to different direct inputs of MPs, some other factors may influence the concentration of MPs on beaches, this includes: 1) overall tidal range and state of tides at time of sampling; 2) weather conditions such as the occurrence of storms over recent weeks immediately prior to sampling; 3) beach morphology; 4) the prevailing wave climate; and 5) sediment grain size and composition. Combinations of these factors, very few of which are accounted for in most MPs studies, confound making comparisons of MPs concentrations on different beaches (GESAMP, 2019).

The abundance of MPs in water in BNP and HNP was lower compared to what we found in coastal sand. Due to constantly changing water mass at the sampling locations, the sampling of MPs via surface water transects creates a "snapshot", which could be largely affected by prevailing winds, currents and weather. Prevailing winds and currents push or blow marine litter and MPs onto beaches where they accumulate close to the high tide and dune/vegetation line (Andrady, 2011; Cole et al., 2011; Wright et al., 2013). Large items and MPs get lodged in the sand, where they breakdown into smaller plastics due to weathering from UV, extreme temperatures, wind or wave action (GESAMP, 2019). In surface waters, the reduced UV exposure and lower temperature slows down the formation of secondary MPs (GESAMP, 2019). These processes probably lead to higher MPs concentrations on beaches compared to the water surface.

A total of 148 "small MPs" was found in the surface water across all three sampling sites of BNP. Most MPs were filaments (133) and no "large MPs" were present. MPs concentrations ranged from a maximum of 0.416 MPs/m^3 at the W1 site to a minimum of 0.096 MPs/m^3 at the W3 site. The W2 site recorded 0.317 MPs/m^3. Blue, green, red, white and brown coloured MPs were identified in coastal surface waters of BNP. A total of 150 "small MPs" were found in coastal waters of HNP. Most MPs were filaments (91) and no "large MPs" were present. MPs concentrations ranged from a maximum of 1.031 MPs/m^3 at the HW1 site to a minimum of 0.878 MPs/m^3 at the HW2 site. Blue, green, red, white and purple coloured MPs were identified in coastal surface waters of HNP. Ronda et al., (2019) reported 0.14 $\pm$ 0.08 items/m^3 synthetic microfibers in the Argentinean continental shelf –including a Marine Protected Area. The reported values in BNP and HNP surface waters are somewhat higher than those Argentinean continental shelf values.

When we consider the three lagoons in BNP (Bundala, Malala and Embilikala), MPs were absent in sediment or water. These three lagoons have not been connected with the ocean for a long time. Bundala lagoon is not connected with the ocean for several years because of sand barriers. Malala lagoon connects with the ocean via a man-made canal. Nevertheless, due to the length of the canal, sea water is not mixing with lagoon water therefore, there are no transport pathways for marine-based debris.

According to Chang et al. (2018), there were around 100 items/m^2 between 5 and 25 mm in BNP. The highest recorded percentage for plastics was 93%, which is comparable with our study. Koongolla et al. (2018), recorded 8 $\pm$ 8 MPs/m^2 at 10 m distance from shore and 97 $\pm$ 93 MPs/m^2 at 20 m distance from shore in Hikkaduwa. Our values were recorded two years later and are somewhat higher which could indicate short-term increases and/or accumulation over time. In India, several MPs studies were conducted, they reported 9 to 178 MPs/m^2 at high tide lines and 2 to 64 MPs/m^2 at low tide lines (Karthik et al., 2018). Jayasiri et al. (2013) found 0.25–282.5 MP/m^2 on Mumbai beaches. The number of MPs observed in this study is comparable with several other global studies; Gray et al. (2018) found 51–441 MPs/m^2 in Winyah Bay and 42–1196 MPs/m^2 in Charleston harbor, USA; Hidalgo-Ruz and Thiel (2013) showed that 1–169 MPs/m^2 in Chile; and Martins and Sobral (2011) noted 1–137 MPs/m^2 on Portuguese beaches.

Whitmire and Bloem (2017) reported MPs presence in 32 sites across national parks in the USA. They found on average 50 to 225 MPs/kg of dry sediment. Those sites included a variety of locations from urbanised areas to remote beaches. Bayo et al. (2019) recorded MPs in a protected coastal area, the Mar Menor lagoon (SE Spain) (53.1 $\pm$ 7.6 items kg^{-1} dry sediments). Masiá et al. (2019) found MPs in eight beaches of the southwest Bay of Biscay (Spain) within Natura-2000 Special Protection Areas for birds (between 145 and 382 particles per kg of dry sand). Ronda et al. (2019) also reported synthetic microfibers (MFs) on the Argentinean continental shelf (including MPAs) with average concentration of 182.85 $\pm$ 115.14 particles per kg of dry sediment and 0.14 $\pm$ 0.08 items per m^{-3} of marine water. However, comparison of these data is always difficult, because of the lack of standardised sampling methods, filter or mesh size used for the analyses, and differing units to express data.

At BNP, MPs were recorded in all turtle nesting areas with high abundance, also in the dune area where turtles tend to nest. Beckwith and Fuentes (2018) reported MPs at northern Gulf of Mexico loggerhead recovery units, with abundance 61.08 $\pm$ 34.61 pieces/m^2. However reported values in turtle nesting areas of BNP in Sri Lanka are much higher than those values. HNP also show considerable level of MPs pollution. Corals and associated flora and fauna can be severely affected by MPs pollution. There are several studies about ingestion of MPs by corals and other diseases of corals which are caused by the presence of plastics and MPs in the surrounding environment (Hall et al., 2015; Lamb et al., 2018). MPs ingestion by cold-water coral reef benthos at the East Mingulay Marine Protected Area (Sea of the Hebrides, Western Scotland) was reported by La Beur et al. (2019).

Silva et al. (2017) reported MPs contamination in fish and mussels in southern coastal waters of Sri Lanka. Sathyadith et al. (2019) also found microplastics in cultured oysters in Kalpitiya Lagoon, Sri Lanka. Polyethylene was found in the gut content of *Sardinella* sp. in the Negombo lagoon, Sri Lanka (Ranatunga and Karunaratna, 2018). All these studies confirm the presence of MPs in the Sri Lankan marine environment and biota. In this study, we have clearly observed the presence of MPs in sediment and water in two Marine Protected Areas. So there is a high possibility that in these two Marine Protected Areas, marine biota (especially fish, turtles, sea birds, corals and associated organisms) is affected by MPs.

3.2. Microplastics in coastal sand: size, shape, polymer composition and oxidation state

MPs were categorized in two size classes: large and small MPs. The average size of MPs in BNP is lower than in HNP (Table 2). BNP is located in a high energy zone, so wave action could accelerate the fragmentation processes. Besides, BNP is located in the dry zone of Sri Lanka with high UV radiation which potentially could increase fragmentation even further compared to HNP which is located in the wet zone of Sri Lanka.

Table 2
Mean size of large MPs in Bundala National Park (BNP) and Hikaduwa Marine National Park (HNP).

Site	High tide line (mm $\pm$ SE)	Dune/vegetation line (mm $\pm$ SE)
BNP	3.14 $\pm$ 0.17	2.96 $\pm$ 0.18
HNP	3.46 $\pm$ 0.16	3.39 $\pm$ 0.43

The shape and polymer type of MPs provide valuable information about their origin. Both BNP and HNP show five different types of shape classes of MPs: fragments, filaments, foams, films and pellets. Overall, fragments and filaments were the most prevalent shapes in BNP while at HNP fragments and foams were more prevalent (Fig. 4). Both filaments and foams can originate from fishing activities. Fishing nets and ropes are a major source for filaments, and foams can be derived from Styrofoam boxes and buoys (OSPAR, 2017). Due to their lightweight, filaments and foams can be transported over long distances. Filaments in BNP could thus have originated elsewhere and arrived via ocean currents. There are two fishing harbours, Hambanthota and Kirindha, rather far away from the BNP, but pollutants disposed there may be transported to the national park via ocean currents.

The chemical identity of the MPs can provide important information about the origin of the MPs. Due to the different chemical and physical properties of these polymers, they are used in different consumer products and industrial processes. The “large MPs”, in both HNP and BNP, were predominantly Polyethylene (PE), followed by polypropylene (PP) and Polystyrene (PS). Polyvinyl chloride (PVC) and Nylon (PA) were also observed, but in minor percentages. Therefore, those last two were grouped under the “other” category (Fig. 4).

At BNP, all sites except for the B3 and the B5 sites display all three polymers. PE is the most common polymer for all of the sites perhaps because of the wide range of PE products in fishing and packaging applications (Figs. 4 and 5). Large MPs were predominately fragments made from PE and PP. In HNP, all of the sites displayed all three polymer types. The percentage of PS (foam) is higher in HNP compared to BNP.

Polymers exposed to sunlight for long periods of time undergo oxidative degradation. The oxidation state of MPs depends on the exposure time to UV light and other factors that accelerate the oxidation. FTIR analysis gives information about the extent of oxidation of MPs as reflected by the absorption peak between 1680 and 1760 cm^{-1}. According to the FTIR spectra of the MPs 39.53% of the “large MPs” in BNP and 36.17% of the “large MPs” in HNP show measurable extent of oxidation. Oxidation of samples of MPs collected from BNP is somewhat higher than those collected in HNP and this perhaps suggest that most of the “large MPs” in BNP reside in ocean water or coastal sand for longer period of time compared to those MPs at HNP. Due to the absence of point sources, most of the MPs in BNP arrived from a distant location. This pathway may take longer and oxidation could happen at the surface waters via UV radiation and oxygenation. Once deposited on the coastline, the high temperature might further accelerate oxidation of MPs. Not only fragments, pellets also show oxidation highlighting their presence in the environment for long times.

3.3. Identification of small MPs using Nile Red staining

We defined the percentage of MPs which were fluorescing with Nile Red dye. In total, 92.44% in BNP and 80.91% in HNP were fluorescent with Nile Red. This confirmed that a high percentage of MPs that were visually identified are indeed plastics. Unlike fragments and foams, films are very thin and two-dimensional. Identifying films below 1 mm turned out to be more difficult because of their transparency, with Nile Red even transparent films stained red and emitted fluorescence under blue light.

4. Conclusion

According to the results of this study, both MPAs are heavily affected by MP pollution. At BNP, a high concentration of MPs was recorded in all turtle nesting areas including the dune areas where turtles tend to nest. The reported MPs values in Sri Lanka are much higher than previously reported values, potentially affecting both hatchlings and adult sea turtles in several ways.

Most of the MPs in BNP are probably arriving on ocean currents, while in HNP local input of MPs appear to be dominant. Fragments and filaments were the most abundant shapes and PE, PP and PS were the most prominent polymer types. Additional, Nile Red analysis showed that most of the visually identified small MPs were in fact plastics. MPs at both sites showed significant levels of oxidation, which led to the conclusion that most of the large (1.1–5.0 mm) MPs remain in the coastal area for long periods of time. BNP showed decreasing MPs abundance from the B1 to the B7 site. This decrease could be caused by the Southwest Monsoon currents.

MPAs are designed to protect associated flora and fauna in that area. Specific rules and regulations have been put in place to protect this environment. Our findings suggest that MPs pollution is significant in both MPAs, despite protection of these areas or the remoteness of the area. This research delivers a first baseline and allows following up on the pollution levels in MPAs by implementing new rules and regulations. Further research is needed to investigate the impacts of MPs on marine organisms and to determine ecological impact to the ecosystems. It is important to determine the underlying processes and pathways e.g. the effect of monsoon currents on the distribution of MPs, because it supplies important information to define measures and ultimately tackle the issue.

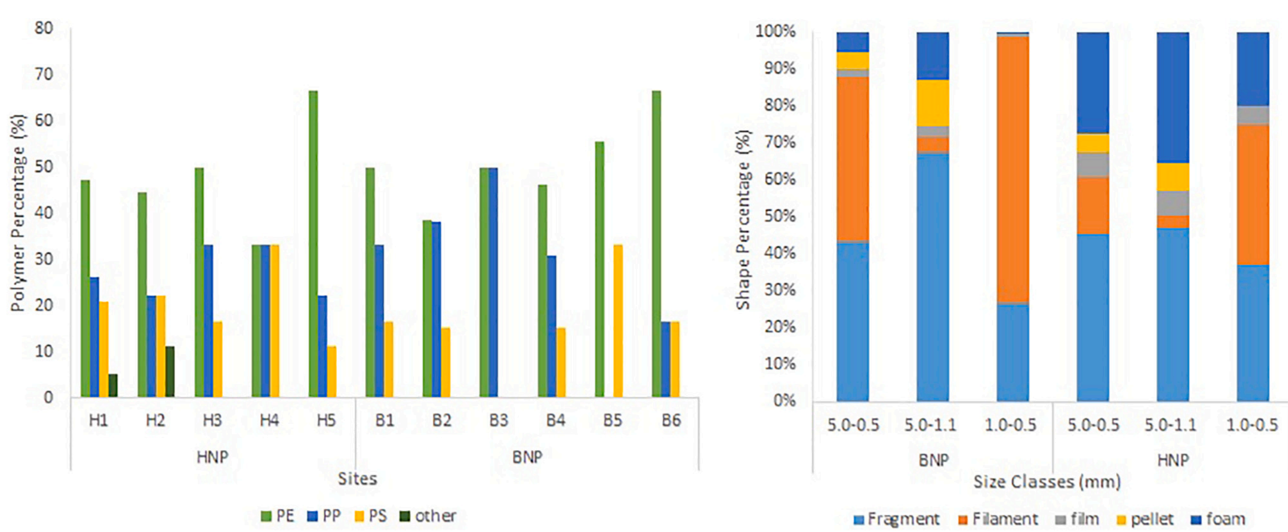

Fig. 4. Large MPs polymer percentage (left) and percentage of shapes of total MPs according to their size category (right) of coastal sand in BNP and HNP.

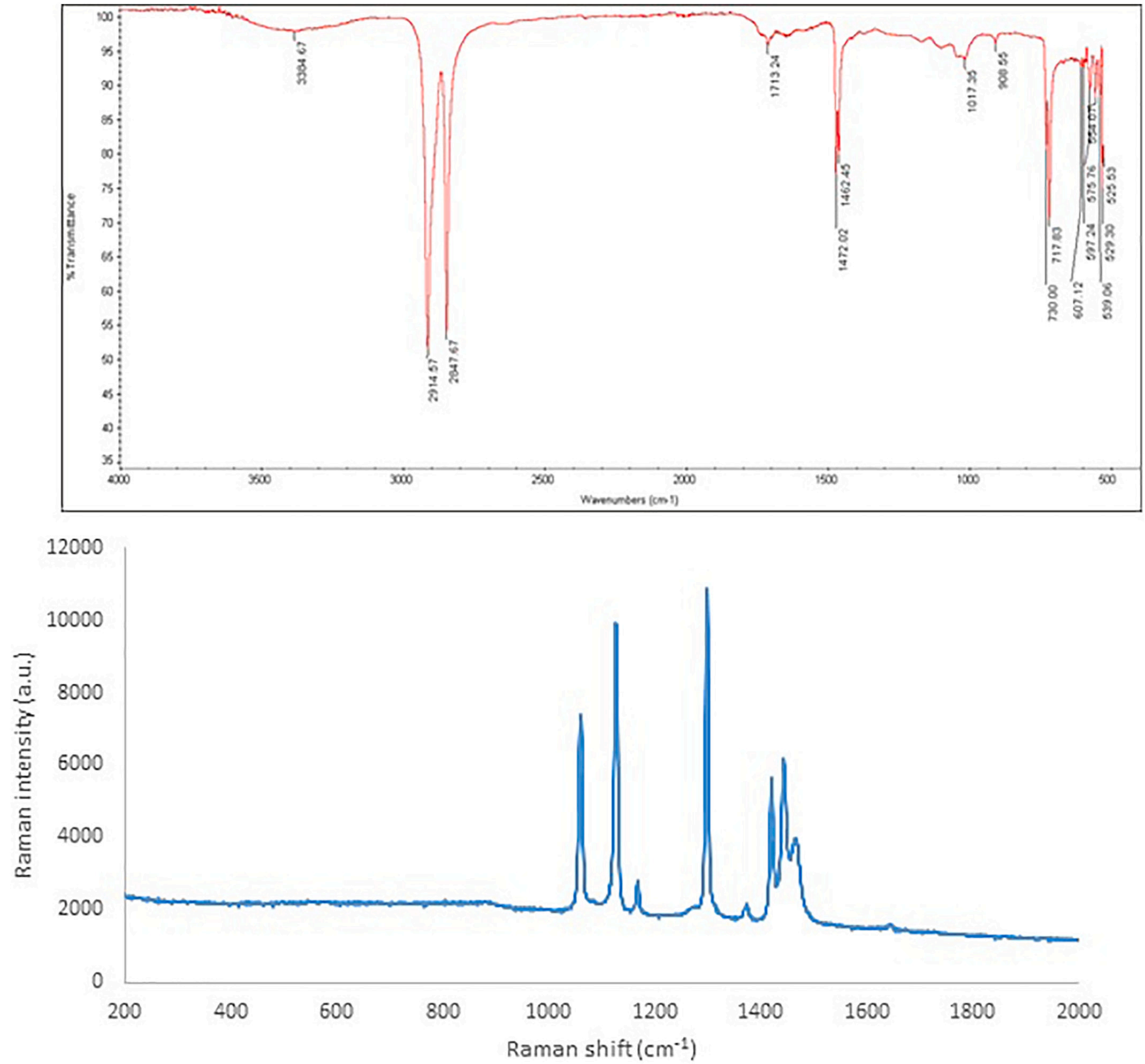

Fig. 5. ATR-FTIR spectra (top) and Raman spectra (bottom) for polyethylene (PE) microplastics sample.

CRediT authorship contribution statement

W.L.S. Sevwandi Dharmadasa: Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **A.L. Andrady:** Conceptualization, Methodology, Validation, Formal analysis, Resources, Writing – original draft, Writing – review & editing, Supervision. **P.B. Terney Pradeep Kumara:** Conceptualization, Methodology, Validation, Resources, Supervision, Visualization. **T. Maes:** Conceptualization, Validation, Writing – review & editing, Funding acquisition, Supervision. **C.S. Gangabadage:** Methodology, Validation, Resources, Supervision.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2021.112462.

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