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SHORT RESEARCH AND DISCUSSION ARTICLE

Micro- and mesoplastic pollution along the coast of Peru

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Abstract
Peru suffers from poor solid waste and coastal management, as well as evidenced plastic pollution in various forms. However, studies in Peru focusing on small plastic debris (i.e., meso- and microplastics) are still limited and inconclusive. Thus, the present study investigated the abundance, characteristics, seasonality, and distribution of small plastic debris along the coast of Peru. The abundance of small plastic debris is predominantly driven by specific locations, where a source of contamination is present, rather than presenting seasonal patterns. Meso- and microplastics were strongly correlated in both seasons (summer and winter), suggesting meso-plastic constantly breaking down as microplastic sources. Additionally, heavy metals (e.g., Cu, Pb) were found in low concentrations (mean concentrations < 0.4%) on the surface of some mesoplastics. Here, we provided a baseline on the multiple factors involving small plastic debris on the Peruvian coast and preliminarily identify associated contaminants.

Keywords Beach · Contamination · Heavy metal · Mesoplastic · Microplastic · Plastic

Introduction

Small plastic debris represents one of the most widespread contaminants worldwide. Although there is no current standardized measurement, small plastic debris is generally classified based on its size (Hartmann et al. 2019). Most studies agree that microplastics (MPs) measure between 1 µm and 5 mm, while mesoplastics (MePs) are between 5 and 25 mm in size, and macroplastics measure > 25 mm (Ghaffari et al. 2019; Olivo et al. 2022). It is known that the extent of plastic pollution, more specifically by MPs, has become present in the food chain of the marine ecosystem, being found in the digestive tract of larger (Kühn and van Franeker 2020; Moore et al. 2020) and smaller animals (Ben-Haddad et al. 2022; Truchet et al. 2021; Vandermeersch et al. 2015), as well as every natural (Abelouah et al. 2022; Benson et al.

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2022; Dioses-Salinas et al. 2020) and urban environments (Hajiouni et al. 2022; Kashfi et al. 2022; Mohammadi et al. 2022; Takdastan et al. 2021).

The coast of Peru faces the Southeast Pacific Ocean, where intense anthropogenic activities take place. It is recognized for its coastal zone development, driven by internationally renowned tourism, aquatic sports, and great diversity of marine species, which are directly linked to successful gastronomic ventures, among other factors. However, recent studies exposed the alarming state of marine litter and MP pollution on beaches along the coast (De-la-Torre et al. 2022b, 2021), potentially threatening the well-being of a vast number of organisms. Up to date, MP studies carried out in Peru are fairly simplistic, generally focusing on a few sampling locations with no temporal analysis. For instance, the study by De-la-Torre et al. (2020) only sampled four adjacent beaches for two consecutive months (March and April). A previous study also investigated MP pollution in only four beaches in Peru, without taking into account the influence of seasonality or a widely distributed geographic area (Purca and Henostroza 2017). Furthermore, the presence of external contaminants, such as heavy metals, on the surface of plastic debris is globally common (Dobaradaran et al. 2018), but has yet to be assessed in Peru. In light of the current context, the present study aimed to provide a baseline of the current state of small plastic debris (MPs and MePs) pollution along the Peruvian coast during two seasons, expanding from the central-southern up to the northernmost coastal regions. In addition, the correlation between the MePs and MPs abundance was investigated. Finally, the presence of heavy metals on the surface of MePs was preliminarily assessed to provide insights concerning the interaction of these two contaminants.

Materials and methods

Eleven beaches were investigated expanding from Tumbes (northernmost region) to Ica (central-southern region). Table 1 summarizes the main characteristics, location, and activities held on each beach. The majority of the beaches are nationally recognized for their recreational tourism activities (sunbathing, swimming, diving, and sports, among others, with the presence of hotels, restaurants, and bars), which are very popular destinations during summer holidays, and artisanal fishing. In the case of S11, the beach belongs to the buffer zone of the Paracas Nature Reserve (PNR), an internationally recognized touristic protected area for its marine landscapes, biota, and activities. While S11 is technically not within the PNR area, the beach is surrounded by the majority of restaurants, hotels, and stores in the region, also exhibiting the presence of artisanal fishing activities.

The 11 beaches were sampled in January 2022 (Summer) and July 2022 (Winter). On the field, surface sand was sampled using a $0.5 \times 0.5\ m^2$ quadrant as described in previous studies (Akkajit et al. 2021; Li et al. 2020). On the supralittoral zone,

Table 1 Description of the studies sites along the Peruvian coast

Code	Beach	Region	Substrate	Coordinates	Main activities
S1	Zorritos	Tumbes	Sand	80°41′17.0"W 3°40′56.9"S	Recreational tourism
S2	Máncora	Piura	Sand	81°03′23.4"W 4°06′19.4"S	Recreational tourism
S3	Paita	Piura	Sand	81°06′45.6"W 5°05′04.6"S	Artisanal fishing
S4	Pimentel	Lambayeque	Sand	79°56′16.2"W 6°50′11.9"S	Recreational tourism
S5	Huanchaco	La Libertad	Sand/boulder	79°07′15.9"W 8°04′43.1"S	Recreational tourism
S6	Puerto Morin	La Libertad	Sand	78°53′52.0"W 8°23′54.4"S	Local recreational and artisanal fishing
S7	Chimbote (Caleta)	Ancash	Sand	78°36′17.6"W 9°04′31.4"S	Intense high-scale and artisanal fishing
S8	Tuquillo	Ancash	Sand	78°11′36.6"W 10°01′00.8"S	Recreational tourism
S9	Chorrillos	Lima	Sand	77°36′50.6"W 11°06′47.7"S	No apparent specific activity
S10	Sombrillas	Lima	Sand	77°01′34.7"W 12°09′24.1"S	Recreational tourism and artisanal fishing
S11	Paracas	Ica	Sand	76°15′02.6"W 13°50′02.0"S	Nature tourism and artisanal fishing activity

the quadrant was randomly placed, and the surface sand was scooped with a metal shovel up to 5 cm in depth. The same procedure was repeated thrice per beach. A 100 m distance was estimated between replicates. The sand was immediately sieved through 4.75 mm and 1 mm nested sieves and the content in each tray was stored in Ziplock bags until further analysis. To separate the MPs and MePs from other content, a saturated NaCl solution ($\rho = 1.2$ g/cm^3) was prepared, prefiltered, and poured into a glass beaker. The contents from each tray were then mixed with the saline solution and the floating MPs and MePs were manually separated with tweezers. Standardized contamination prevention measures (e.g., use of laminar flow cabinets, procedural blanks, thorough cleaning procedures) were not necessary, as only the larger MP fraction (> 1,000 µm) was assessed and effectively identified by the naked eye. In any case, a hot needle was used to test a suspected particle when necessary. MPs and MePs were stored in aluminum foil envelopes until further analysis.

MPs/MePs were classified by their main color and shape (fragment, film/sheet, fiber/liner, or pellet/sphere) following (Hartmann et al. 2019). Considering the remarkable abundance of expanded polystyrene (EPS) particles on Peruvian beaches (De-la-Torre et al. 2020), an additional shape classification was added (foams) to describe microporous particles.

Forty MPs representing the five morphotypes (8 of each) were selected for FTIR analysis, as described in our previous study (De-la-Torre et al. 2020). The analysis was performed on a Perkin Elmer Frontier™ FT-IR coupled with a universal ATR apparatus at wavelengths between 500 and 4000 cm^{-1} and 30 scans per reading. The obtained spectra were automatically compared with the IR spectral library. The polymer with the highest percentage of similarity was selected and accepted with a match > 75% (Stockin et al. 2021).

Twenty randomly selected MeP particles were qualitatively analyzed by EDX spectrometry, as described in our previous study (De-la-Torre et al. 2022d). Elemental analysis was performed on an EDX-800HS (Shimadzu, Japan) spectrometer equipped with a Si (Li) semiconductor detector under a vacuum atmosphere. The elements ranging from Na to U were detected and the results were expressed in percentages.

Plastic debris abundance was analyzed in terms of MP or MeP particles per 0.25 m^2. Two-way ANOVA tests were conducted to compare MP and MeP abundance between seasons and sampling locations and the interaction between the two factors. The analyzes were followed by Sindak's multiple comparisons tests to compare the abundance between seasons for each sampling location independently. In order to visually analyze the data, multidimensional scaling (MDS) graphs were constructed based on the abundance of different MP or MeP morphotypes. A Pearson test followed by a simple linear regression was applied to investigate the correlation between MeP and MP abundance in both seasons. Statistical significance was set to 0.05. The analyzes were carried out with GraphPad Prism (version 8.4.3 for Windows) and the MDS graphs were constructed with PRIMER 6 (version 6.1.16).

Results and discussion

A total of 2128 MPs and 398 MePs were extracted and counted (details are available Table S1 and S2). In this sense, MPs (1000 – 5000 µm) were the most abundant particles found along the Peruvian coast. The sites with the highest levels of MePs and MPs were S7 and S9, respectively, in both seasons, where intense high-scale and artisanal fishing are the predominant activities.

In the summer, the mean MP abundance ranged from 0.67 ± 0.58 (S8) to 183.00 ± 60.51 MPs/0.25 m^2 (S9), and mean MeP abundance ranged from 0.33 ± 0.58 (S6) to 34.33 ± 7.51 MePs/0.25 m^2 (S7). In the winter, the mean MP abundance ranged from 0.33 ± 0.58 (S2 and S6) to 138.00 ± 36.35 MPs/0.25 m^2 (S9), and mean MeP abundance ranged from 0.00 ± 0.00 (S8) to 29.33 ± 6.66 MePs/0.25 m^2 (S7). In previous studies from Peru, mean MP (1 – 5 mm) abundances were estimated at 43.5 MPs/0.25 m^2 in four beaches from Lima (De-la-Torre et al. 2020), and a maximum of 115.8 MPs/0.25 m^2 in another study (Purca and Henostroza 2017). In general terms, these concentrations may be one of the highest from the SE Pacific coast, considering that the mean MP concentration in continental Chile has been reported at approximately 6.75 MPs/0.25m^2 (Hidalgo-Ruz and Thiel 2013). Overall, Peru remains one of the least studied countries in terms of MP pollution in the region (Orona-Návar et al. 2022).

In the case of MPs, the 2-way ANOVA revealed that the combined effect of sample location and season on MP abundance (MPs/0.25 m^2) was not statistically significant ($F(10, 44) = [1.178]$, $p = [0.3311]$). However, simple main effects analysis showed that sampling location had a statistically significant effect on abundance ($F(10, 44) = [49.90]$, $p = [< 0.0001]$), while season did not ($F(1, 44) = [2.160]$, $p = [0.1488]$). In the case of MePs, the combined effect of sample location and season was not statistically significant ($F(10, 44) = [0.8122]$, $p = [0.6184]$). Similarly, the simple main effect analysis showed that sampling location had a statistically significant effect ($F(10, 44) = [62.46]$, $p = [< 0.0001]$), and season did not ($F(1, 44) = [2.738]$, $p = [0.1051]$). Furthermore, Sidak's multiple comparisons test showed no statistically significant differences (≥ 0.05) in the abundance between seasons for any sampling location for both MPs and MePs. Unexpectedly, MeP and MP abundance remained statistically similar in both seasons in every analyzed beach. These results are surprising, considering that most beaches (e.g., S1, S2, S4, and S5, among others) are very popular destinations during the summer seasons, which can be expected as a direct source of plastic litter. Regardless, it is likely that beach cleaning and maintenance efforts are insufficient to eliminate small plastic debris (< 25 mm), thus, resulting in a possible "plastic debris stock" allocated on the supralittoral zone enduring across seasons.

Concerning morphotypes, fragments were the dominant MPs shape (53.0% and 47.6% in the summer and winter, respectively), followed by foams (20.7% and 27.4% in the summer and winter, respectively), fibers/lines (13.7% and 10.6% in the summer and winter, respectively), sheet/films (7.8% and 10.8% in the summer and winter, respectively), and pellets (4.8% and 3.6% in the summer and winter, respectively) (Table S3). In the case of MePs, fibers/lines were the dominant shape (46.6% and 52.0% in summer and winter, respectively), followed by fragments (23.5% and 31.1% in summer and winter, respectively), sheet/films (23.5% and 11.3% in summer and winter, respectively, and foams (6.3% and 5.6% in summer and winter, respectively) (Table S4). MeP spheres were not found at all. MPs morphotypes per sampling site in both seasons are displayed in Fig. 1. Fragments are generally regarded as the most abundant shapes in Latin America. For instance, in Mexican beaches, rigid and semirigid (fragments) MPs (1 – 5 mm) dominated with 56%, followed by foams (15%) and fibers (11%) (Alvarez-Zeferino et al. 2020), as well as in Uruguay (Rodríguez et al. 2020), and Peru (De-la-Torre et al. 2020; Purca and Henostroza 2017). However, studies investigating small MP fractions (< 1 mm and < 0.5 mm), mostly agree that fibers are the most common type (Abelouah et al. 2023; Hajji et al. 2023; Truchet et al. 2022), which puts into perspective the influence of methodological choices.

As is shown in Fig. 2, white MPs were predominant in both seasons (32.5% and 28.4% in the summer and winter,

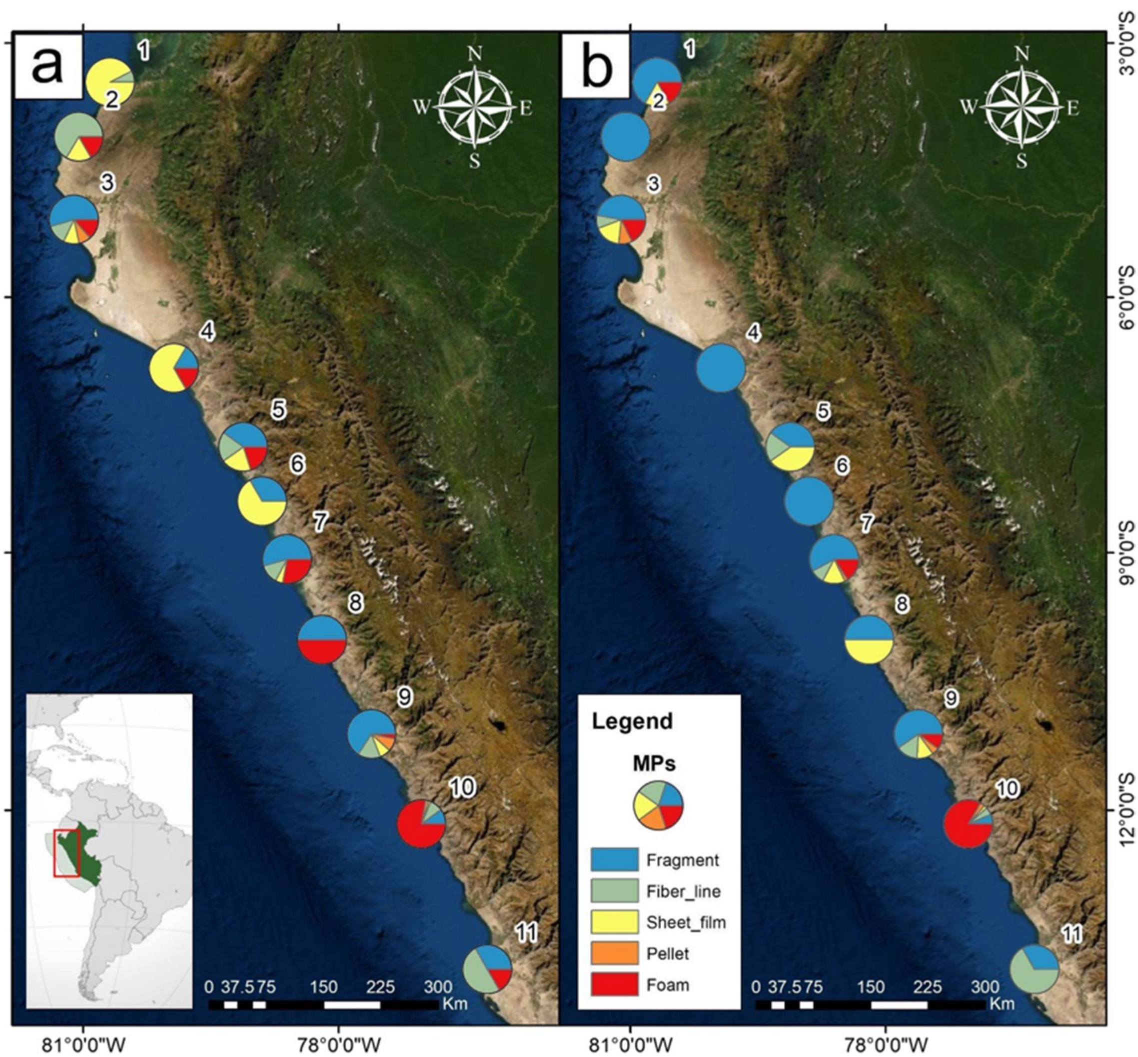

Fig. 1 Map of central-northern Peruvian coast displaying the proportion of microplastic shapes at each sampling location during the summer (**a**) and winter (**b**) seasons. Labels indicate the sampling site. The legend applies to both maps

respectively) (Table S5). This tendency was reflected for MePs only in the summer with a proportion of 36.2%, while green was the predominant color (36.2%) in winter (Table S6) Fig. 2 a-d displays the color distribution of MPs and MePs in both seasons. In addition, Fig. 2 e, and f display the violin plots of MPs and MePs abundances, respectively. The colors white, blue, green, and red are widely predominant in MPs across studies in Latin America and elsewhere (Fernández Severini et al. 2019; Garcés-Ordóñez et al. 2019; Pazos et al. 2018), which are indicative of the type of commercial products that breakdown in the environment.

A significant amount of large solid waste (visible to the naked eye), which could be poorly degraded, explaining the relatively high MeP abundance in S7. On the other hand, S9 shows a greater number of smaller particles (MPs) that are not directly visible despite their high abundance. This may be due to solid waste emission and weathering time resulting in plastic fragmentation, assuming plastics in S9 spend more time in the beach area. Both MP and MeP contributions to plastic pollution in beaches have been related to anthropogenic activities such as tourism, fishing, city discharges, and industrial production (Claessens et al. 2011; Stolte et al. 2015) in addition to high levels of population density as discussed by Pedrotti et al. (2016). This could explain why both S7 and S9 are the ones with the highest amount of MePs and MPs since both Playa Caleta (S7) and Playa Chorrillos (S9) are among the most populated in both seasons. Plastic debris could also be the result transported by ocean currents (Su et al. 2022). Wind orientation could also be a factor in the accumulation of plastic debris on beaches (Monteiro et al. 2018). Windward beaches, predominantly affected by winds, wave action, and ocean currents, as the Peruvian beaches, generally present a higher quantity of plastic particles. Studies have suggested that wet seasons are characterized by higher MP loads into the oceans due to the increase in the river flow (and, consequently, transport

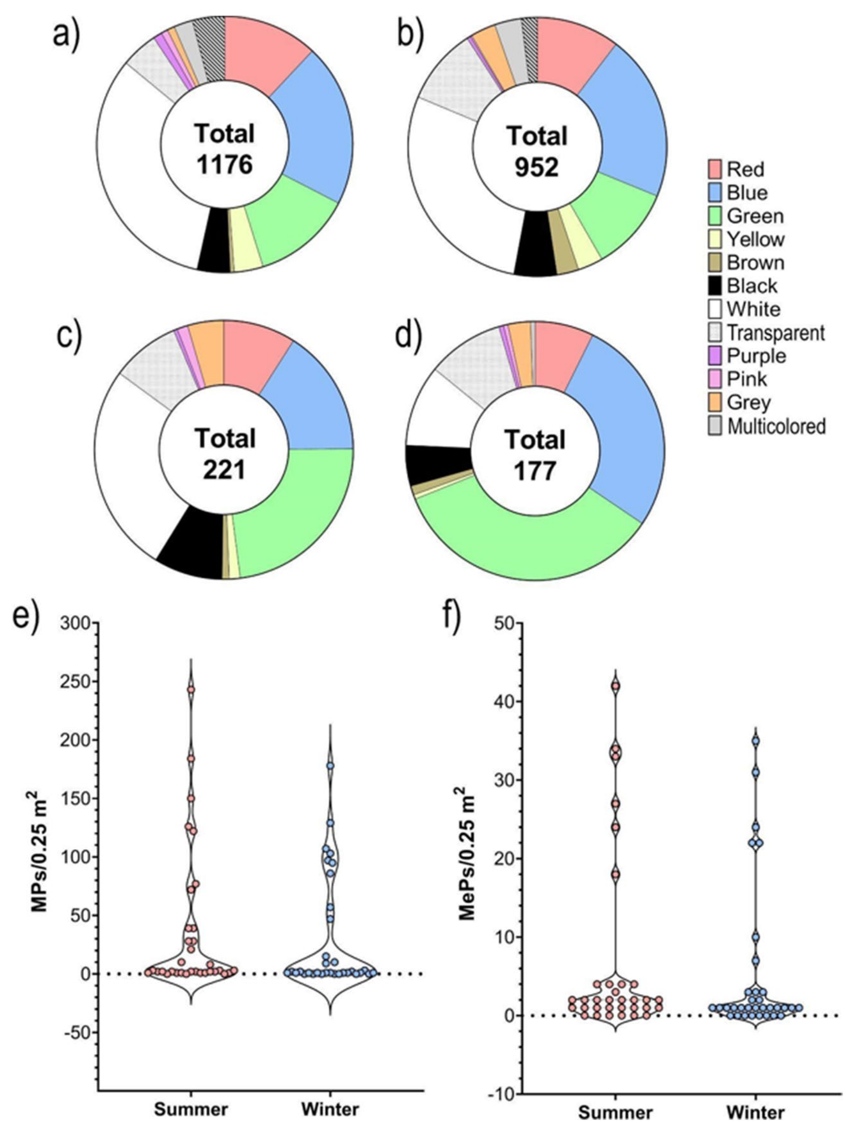

Fig. 2 Pie charts displaying the different colors of MPs during summer (**a**) and winter (**b**), and MePs during summer (**c**) and winter (**d**). Numbers at the center of the pie chart indicate the total number of MPs/MePs counted. Violin plots with individual values of MPs (**e**) and MePs (**f**) in both seasons state the distribution of MP and MeP abundance for both seasons, where each dot represents a repetition for each sampling station

of land-based MPs) (Rakib 2023), but this is not always the case (Wang et al. 2021). The seasonality of MPs is governed by multiple variables that are unique to each geographic area (Sá et al. 2022), such as oceanographic and riparian characteristics (e.g., river flow, surface currents) and social aspects (e.g., beach cleaning, waste dumping).

The MDS analysis showed clear groups based on sampling location (Fig. 3 a) with no particular contribution of seasonality. The previously discussed predominance of MePs and MPs (all morphotypes) in S7 and S9 can be observed by the formation of S9 and S7 clusters in the direction of the morphotype vectors. Other clusters formed by multiple sampling locations and seasons indicated a relatively similar MPs/MePs concentration across sites. The lack of seasonal variation is corroborated by the bar graphs in Fig. 4.

Pearson's correlation results showed a strong and statistically significant ($p = < 0.0001$) positive correlation between MeP and MP abundance ($R^2 = 0.6581$, $N = 66$). Figure 5 displays a scatter plot with individual values. According to the simple linear regression, the relationship between MeP and MP abundance can be explained by Eq. 1:

$$y = 0.1563x + 0.9908 \quad (1)$$

The degradation and fragmentation mechanisms of plastic debris are well-known (Andrady 2022; Andrady et al. 2022). The formation of secondary MPs can be explained by a series of chemical changes induced mainly by sun exposure (photo-oxidation and changes in crystallinity), subsequent embrittlement of the material, and fragmentation by

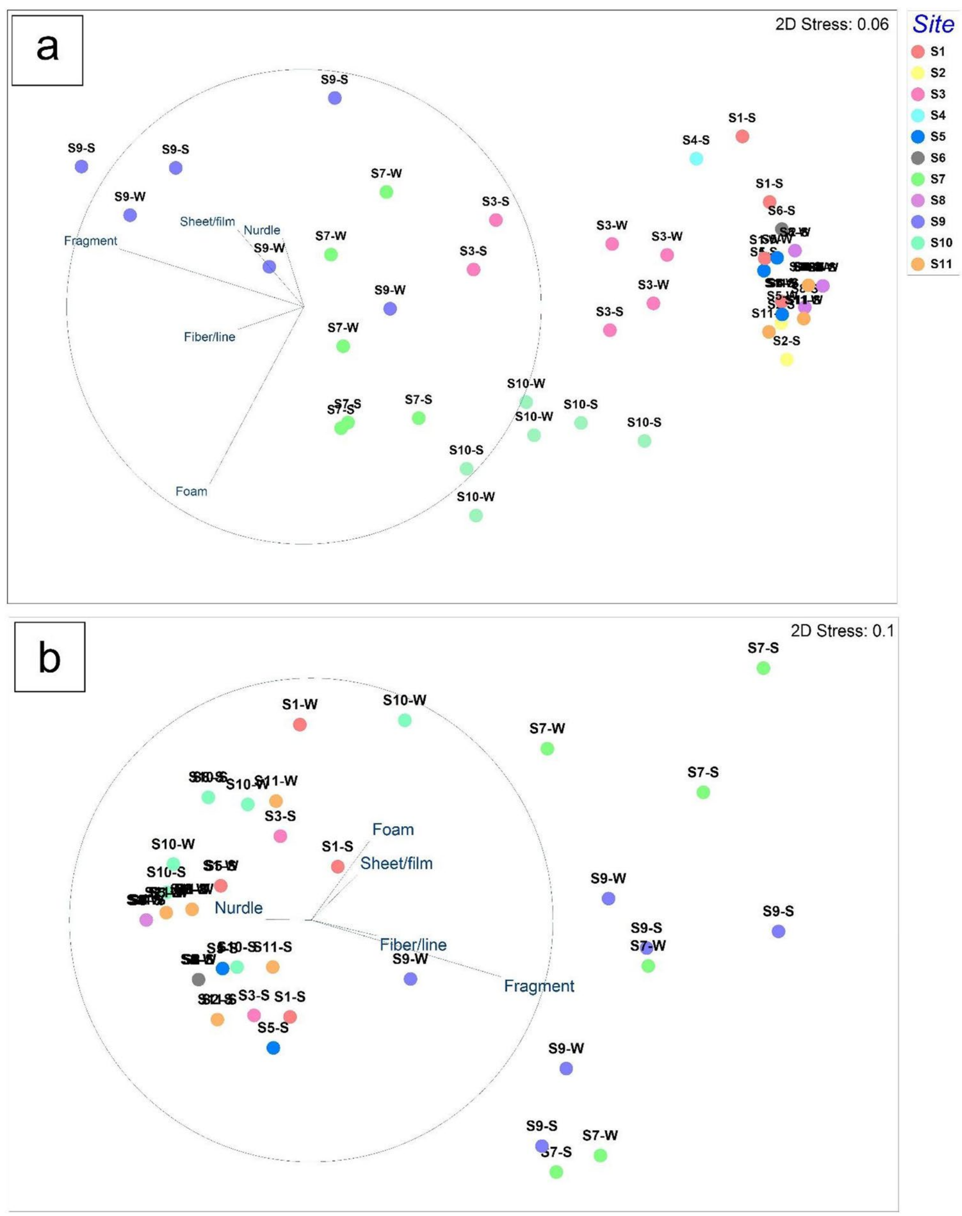

Fig. 3 MDS graphs of MPs (**a**) and MePs (**b**) abundance. Vectors indicate morphotypes

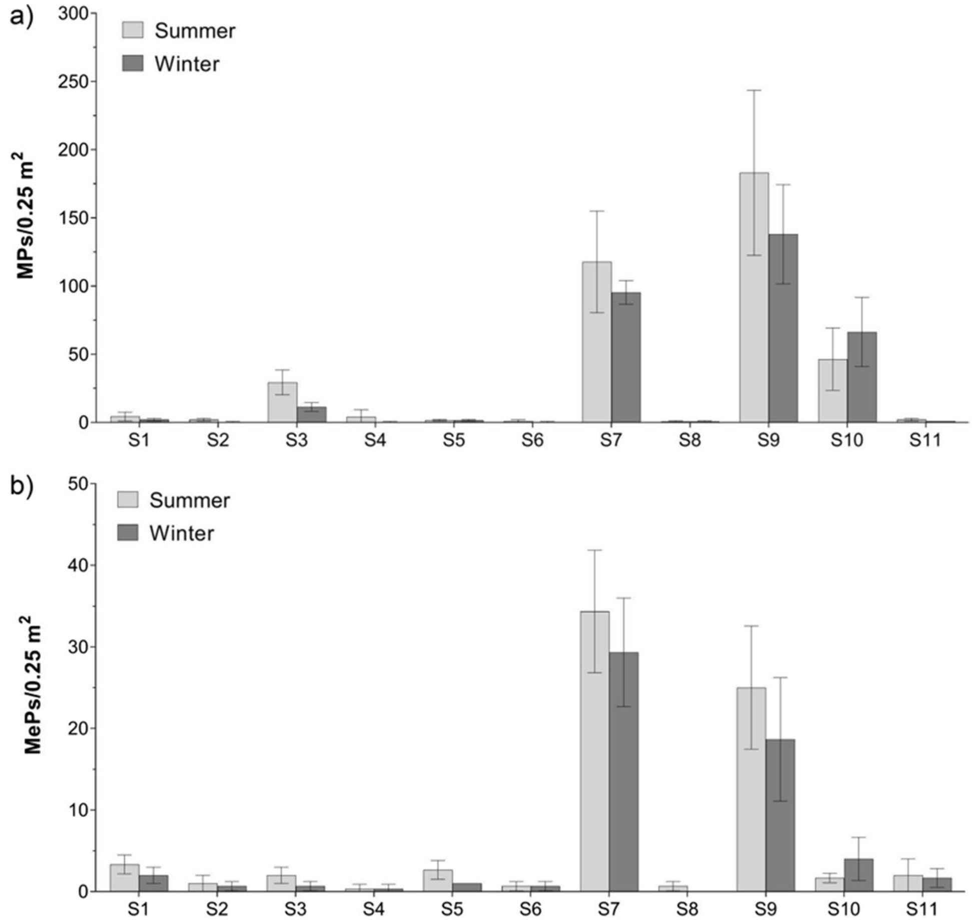

Fig. 4 Mean MP (**a**) and MeP (**b**) concentrations across sampling sites and locations. In both summer and winter seasons. Error bars indicate standard deviation

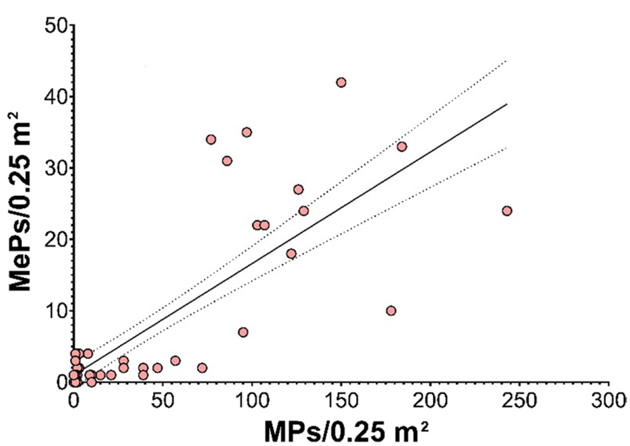

Fig. 5 Scatter plot showing paired MeP and MP abundance data across beaches and seasons and the best-fit line (simple linear regression) with 95% confidence bands

an external mechanical stressor (Deng et al. 2021; Tziourrou et al. 2021). Previous attempts to investigate the relationship among small plastic debris of different sizes displayed similar results to the present study (Manullang 2019). Although field-based studies are required to better understand the fragmentation process of small plastic debris, our results suggest that MePs are continuously breaking down into MPs at variable rates.

The results of the present study are comparable to those in other Latin-American countries, as displayed in Table 2. Most studies focused on analyzed MPs defined by their most popular size range (< 5 mm). However, the presence of MePs cannot be neglected and should be incorporated in small plastic debris surveys as a mandatory category, as it can show strong relation as sources of secondary MPs.

In the present study, a total of six polymers were identified (Table S8). The most predominant polymers were HDPE and PS (25.0% each), followed by PP (17.5%), PET (15.0%), LDPE (12.5%), and Nylon (5.0%). Fragments presented some polymer diversity, consisting of PP, PET, HDPE, PP, and PS, while fibers/lines were composed of PET, PP, or Nylon. On the other hand, all pellets and foams were composed of HDPE and PS, respectively. Lastly, the sheet/film category was composed of LDPE, PET, or PS. Some representative polymers with their respective FTIR spectrum are displayed in Fig. 6. Analyzing both MP morphotype and polymeric composition allows researchers to suggest possible sources of contamination. For instance, the

Table 2 Plastic debris studies in beaches from Latin-American countries

Country	Abundance (MPs/m^2)	Main type	Main color	Size range	Reference
Chile (Easter Island)	805	Fragments	**	1 – 10 mm	(Hidalgo-Ruz and Thiel 2013)
Chile	27				
Uruguay	25	Fragments and pellets	Opaque	< 20 mm	(Lozoya et al. 2016)
Lesser Antilles	276	Fibers	**	0.3 – 5 mm	(Bosker et al. 2018)
Mexico	31.7 – 545.8	Fragments	White	0.5 – 5 mm	(Alvarez-Zeferino et al. 2020)
Panamá	123.75	Fragments	White and colorless	1 – 5 mm	(Delvalle de Borrero et al. 2020)
Peru	174.10	Foams	White	1 – 5 mm	(De-la-Torre et al. 2020)
Brazil	2.4 – 30.4	Fragments	White	0.15 – 5 mm	(Maynard et al. 2021)
Peru	**128.96**	**Fragments**	**White**	**1 – 5 mm**	**This study**
Peru	**24.12**	**Fibers**	**Green**	**5 – 25 mm**	

** not disclosed

only Nylon-based MPs were monofilament lines, which were most likely derived from fishing gear. Also, the thread-like morphology of green fibers (e.g., Fig. 6 a) composed of PP suggests that they are derived from the breakdown of large braided fishing nets. Textiles identified as PET are most likely associated with clothing, as polyester is one of the most widely produced synthetic fabrics (Dalla Fontana et al. 2020). Further, PS foams (e.g., expanded PS) are commonly used for food packaging or insulating materials (Zhao et al. 2022). In our previous study, the dominance of PS foams on beaches of Lima, Peru, was attributed to food PS food packaging delivered by takeaway food kiosks (De-la-Torre et al. 2020). Other MPs, such as white and yellowish pellets (primary MPs) suggest recent and aged, respectively, with a possible spill that may have occurred offshore (Karlsson et al. 2018). With greater polymeric diversity and possible sources, fragments and sheet/films could derive from a vast number of commercially available products, such as single-use plastic bags (resulting in LDPE MP film), water bottles (resulting in PET MP sheets), and many possible solid plastic structures and materials that may break down into small fragments of various colors and polymeric compositions. A recent review of MP studies in Latin America showed that the majority of studies reported PE (40%), PP (17%), and PET (15%) as the dominant polymer types across environmental compartments and species (Kutralam-Muniasamy et al. 2020), which is in agreement with our findings.

Table S9 displays the results of the EDX analysis. Some elements of concern, such as Cr, As, Cd, and Hg, were not detected in any of the samples. However, Cu and Pb were

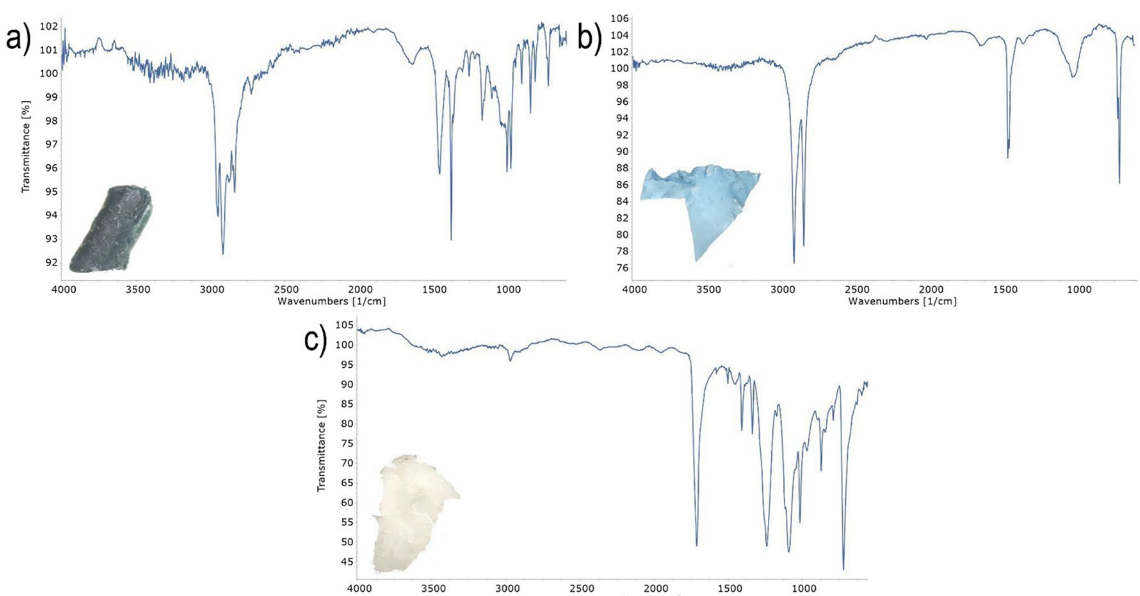

Fig. 6 FTIR spectra of a PP-based black fragment (a), LDPE-based blue film (b), and PET-based sheet

found in 65 and 10% of the samples, respectively (e.g., Fig. 7). The mean percentage of Cu and Pb, when detected, was 0.38 and 0.11%, respectively. Other elements commonly found in the marine environment were also detected, such as Si, Al, Fe (associated with lithic particles), Na, Cl, Ca, Mg, S, and K, among others (associated with suspended particles and dissolved salts in seawater) (De-la-Torre et al. 2022a).

MPs can be a medium for heavy metals in aquatic ecosystems (Liu et al. 2022b; Torres et al. 2021). The absorption of trace metals (e.g., Pb, Cu, Cr, and Cd) has been suggested to be attributed to O-containing functional groups, π-π interactions, and halogen atoms (Liu et al. 2022a). Moreover, changes in characteristics in aged PP pellets that have been exposed to UV radiation have shown to have a higher heavy metal adsorption capacity (Lin et al. 2021). The environmental variables of the surrounding media, such as the pH, salinity, and ionic strength, play an important role in MP absorption (Joo et al. 2021). Contaminated MPs are able to be transferred through higher trophic levels, ultimately reaching human beings (De-la-Torre et al. 2023; Rakib et al. 2023). The presence of MPs in foods will inevitably put into question whether heavy metal uptake is increased (Liu et al. 2022b). For instance, Sarkar et al. (2021) reported the presence of heavy metals, such as As, Cd, Cr, Cu, and Pb, in MPs in fish meat. On the other hand, toxicity studies have shown that co-exposure to MPs and heavy metals (i.e., Cd) induced higher toxicity in plants (Wang et al. 2020). However, the resulting toxicity on humans is poorly understood.

The presence of MPs and heavy metals in the sea may be due to everything from sewage discharge to antifouling paints (Pan and Wang 2012). On the other hand, other elements may suggest the presence of additives commonly used in plastics, such as TiO_2 as a brightening agent (Singh and Bharati 2014). It has been reported that trace metals are found at higher concentrations on MPs recovered from highly anthropogenically altered areas, while PS MPs had a higher affinity than PP and LDPE (Fajković et al. 2022). Interestingly, it has been reported that Pb was found in PVC litter at significantly higher concentrations than in other types of litter in Japan (Nakashima et al. 2012).

Limitations

Several limitations should be acknowledged in the present short communication. For instance, only the larger MP fractions are assessed, despite small MPs (e.g., < 500 µm) being usually the most abundant (De-la-Torre et al. 2022c).

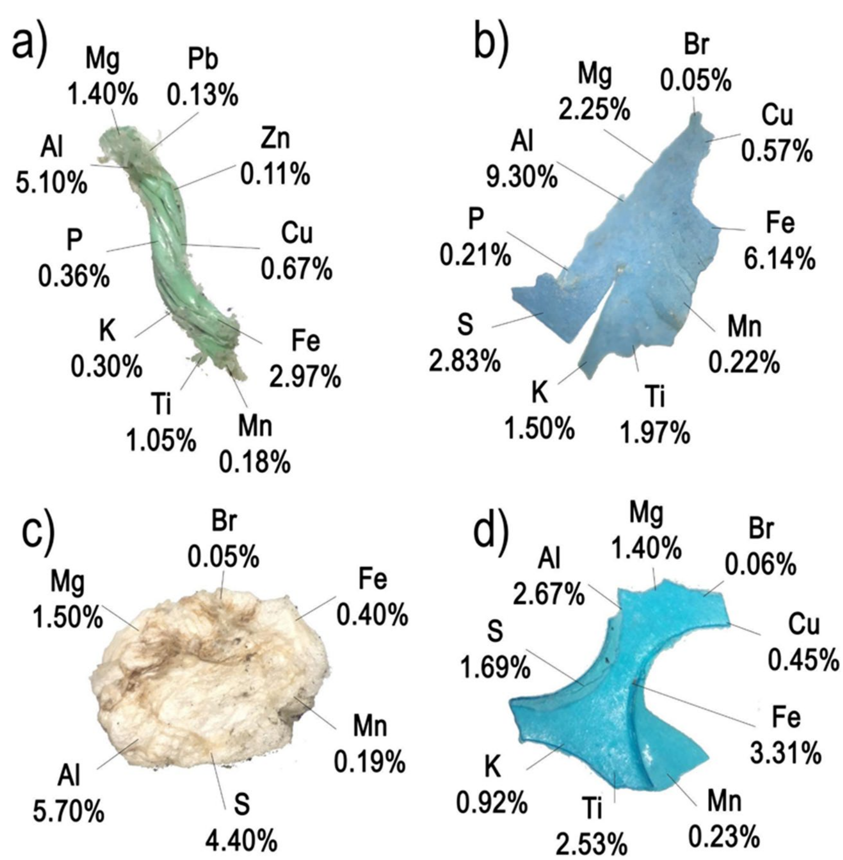

Fig. 7 Content of heavy metals and other elements on the surface of MeP green fiber (**a**), blue sheet (**b**), white foam (**c**), and blue fragment (**d**). Elements with high percentages that are commonly found in the marine environment, such as Ca, Na, Cl, or Si, were not included

Regardless, finding MeP-MP correlations across well-distributed sampling locations displays a novel understanding of the possible link between large and small plastic debris. It is recommended, however, that future studies include the smallest MP fractions, as well as nanoplastics (< 1 µm), into the size-dependent distribution analyses by applying standardized methodologies and quality controls (Dehaut et al. 2019). Furthermore, only a small fraction of the MPs found were analyzed by FTIR and EDX spectroscopy due to the analytical challenges experienced in various developing countries, such as Peru (Kutralam-Muniasamy et al. 2020). To overcome this limitation, research groups must seek international collaborations with shared objectives, which could provide access to advanced equipment and larger-scale studies with comprehensive approaches. Given that one important objective of the present study was to investigate the correlation between MePs and MPs, we believe that focusing on only larger MPs was beneficial because plastic particles can be identified by the naked eye with higher precision. Regardless, the next steps in small plastic debris investigation should incorporate physical and chemical analyzes to find the link between macro-, meso-, and microplastics.

Conclusions

The current state of small plastic debris pollution along the coast of Peru was investigated. Overall, MPs and MePs abundance showed site-specific accumulation preferences rather than seasonal variations, as well as a strong correlation between these two variables. This may be due to the long-term fragmentation process that small plastic debris undergoes, ultimately becoming secondary MPs. The morphology and polymeric composition of MPs provided insights into their possible sources, such as fishing gear, textiles, and food packaging. Elemental analysis of recovered MePs showed the presence of possible trace metals of concern, such as Cu and Pb, in small percentages, in addition to elements associated with lithic and organic material from the marine environment. Further research focusing on field-based studies aiming to understand small plastic debris fragmentation supported by physical and chemical analyses is encouraged.

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Data availability Data will be available on request.

Declarations

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