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Potential microplastic pollution: an invisible threat to the success of coral reef restoration efforts

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ABSTRACT

Introduction: Plastic particles are pollutants in the ocean that are ingested by aquatic organisms, including corals, causing negative effects on their reproduction, growth, nutrition, and survival. The increased urban development, as well as the tourist use of coral reef sites, has heightened their presence, increasing the vulnerability of coral communities, threatening their survival, particularly in sites where coral restoration programs are being implemented.

Objective: Evaluate the presence of potential microplastic (pMPs) particles in the marine sediment in three sites: Playa del Amor and Zona de Restauracion, located in an insular Natural Protected Area with high and low touristic pressure, respectively, but with a coral restoration program implemented, and Las Virgencitas with low touristic and fishing activities.

Methods: Sediment samples were collected at three sites. The abundance and characteristics of pMPs, such as size, shape, color, and weight, were determined.

Results: Evidence of pMPs is observed at all sites, with sizes ranging from 5 to ≤ 600 µm. The highest abundance was recorded at Playa del Amor (0.58 pMPs/g) and the lowest at Las Virgencitas (0.029 pMPs/g). A total of five types of pMPs were identified (fibers, fragments, films, foams, and fiber bundle), with fibers being the most predominant form at all three sites (> 90 %). Regarding shapes, some were found in low abundance, such as foam and films at Playa del Amor, and fiber assemblages exclusively at the Zona de Restauracion. The most abundant colors were blue and black. Sizes varied among sites, with the widest range found at Playa del Amor.

Conclusions: The presence of pMPs at both highly visited sites and those categorized as having low human impact suggests that tourism is one of the most important vectors for the introduction of pMPs; however, indirect carriers, such as rainwater runoff, river flow, and wind transport, should be considered. The constant influx of pMPs increases the vulnerability of coral reefs and, therefore, the conservation and management strategies. Furthermore, these negative effects can escalate from a local to a regional scale, making it necessary to promote mitigation measures that prevent these potential pollutants from entering the water column.

Key words: pollutants; restoration; coral community; touristic hotspot; anthropogenic stressors.

RESUMEN

Potenciales contaminación por microplásticos: una amenaza invisible para el éxito de los esfuerzos de restauración de los arrecifes de coral

Introducción: Las partículas plásticas son contaminantes en el océano que son ingeridas por organismos acuáticos, incluyendo corales, causando efectos negativos en su reproducción, crecimiento, nutrición y supervivencia. El incremento del desarrollo urbano, así como el uso turístico de sitios de arrecifes de coral, ha aumentado su presencia, incrementando la vulnerabilidad de las comunidades coralinas, amenazando su supervivencia, particularmente en sitios donde se están implementando programas de restauración de corales.
Objetivo: Evaluar la presencia de potenciales partículas de microplásticos (pMPs) en el sedimento marino en tres sitios: Playa del Amor y Zona de Restauración, ubicados en un Área Natural Protegida insular con alta y baja presión turística, respectivamente, pero con un programa de restauración de corales implementado, y Las Virgencitas con baja actividad turística y pesquera.
Métodos: Se recolectaron muestras de sedimento en tres sitios. Se determinó la abundancia y características de pMPs, tales como tamaño, forma, color y peso.
Resultados: Se observa evidencia de pMPs en todos los sitios, con tamaños que van desde 5 hasta ≤ 600 µm. La mayor abundancia se registró en Playa del Amor (0.58 pMPs/g) y la menor en Las Virgencitas (0.029 pMPs/g). Se identificaron un total de cinco tipos de pMPs (fibras, fragmentos, películas, espumas y conjunto de fibras), siendo las fibras la forma más predominante en los tres sitios (> 90 %). En cuanto a las formas, algunas se encontraron en baja abundancia, como la espuma y las películas en Playa del Amor, y los ensambles de fibras exclusivamente en la Zona de Restauración. Los colores más abundantes fueron el azul y el negro. Los tamaños variaron entre los sitios, encontrándose el rango más amplio en Playa del Amor.
Conclusiones: La presencia de pMPs tanto en sitios altamente visitados como en aquellos categorizados como de bajo impacto humano sugiere que el turismo es uno de los vectores más importantes para la introducción de pMPs; sin embargo, se deben considerar los portadores indirectos, como la escorrentía pluvial, el flujo de los ríos y el transporte eólico. La entrada constante de pMPs incrementa la vulnerabilidad de los arrecifes coralinos, y por lo tanto las estrategias de conservación y manejo. Más aún, estos efectos negativos pueden llevar de una escala local a regional, por lo que es necesario promover medidas de mitigación que eviten la entrada de estos potenciales contaminantes a la columna de agua.

Palabras clave: contaminantes; restauración; comunidad coralina; zona turística; estresores antropogénicos.

INTRODUCTION

Microplastics (MPs) are considered inorganic pollutants with particle sizes ranging from 1 to 5 000 µm (Soursou et al., 2023). Their origin is entirely associated with human activities and can be primary sources such as cosmetic, medical, and textile products (Flores-Cortés & Armstrong-Altrin, 2022; Napper & Thompson, 2016) or secondary, produced by the mechanical, photolytic, or chemical degradation of larger plastic products such as bottles, bags, and fishing nets (Flores-Cortés & Armstrong-Altrin, 2022; Thompson et al., 2009). Microplastics enter the marine environment through direct inputs of solid waste and by hydrodynamic and atmospheric transport processes, including surface and subsurface currents, wave action, wind, storm events, and seasonal runoff (Cózar et al., 2014; Lutz et al., 2021; Ramírez-Álvarez et al., 2020; Rey et al., 2021; Rios-Mendoza et al., 2021). The accumulation of small plastic particles or microplastics in the ocean has been recorded since the middle 70´s (Morris et al., 1980); however, it was not considered a major problem until the term MPs was defined by Thompson et al. (2004), who reported and classified microscopic fragments and fibers in sediments from beaches, estuaries, and subtidal zones.

MPs accumulate in solid substrates, as well as in the air and the water column. Marine sediments serve as a major reservoir for the accumulation of organic matter, nutrients, and a wide range of pollutants, including plastic particles (Kalev & Toor, 2018). The storage potential is influenced by the particle's density and residence time in the water column, since microbial adhesion and hydrodynamic forces facilitate its sedimentation and, occasionally, its incorporation into seabed sediments (Lobelle & Cunliffe, 2011); also, the grain size affects the retention, as fine sediments have a higher accumulation rate than larger grain size (Lozano-Hernández et al., 2024; Vermeiren et al., 2021) and the oceanographic conditions as currents and waves can also retain the MPs in the water column or promote their sinking (D'Hont et al., 2021; Rey et al., 2021).

Regardless of their deposition site, microplastics can enter organisms through direct or indirect ingestion and bioaccumulate, particularly by the suspension-feeders, which are among the most vulnerable organisms (Egbeocha et al., 2018; Thompson et al., 2009). The negative effects on both vertebrates and invertebrates include reduced food intake, internal injuries, and intestinal obstruction, leading to malnutrition due to pseudo-satiety, as well as an increase in energy demand during digestion and waste expulsion (Cole et al., 2015; Watts et al., 2015). In addition, plastic particles can act as vectors for other persistent organic pollutants, becoming a secondary driver that can further compromise the fitness of the marine organisms (Andrady, 2011; Browne et al., 2007; Thompson et al., 2004). In a cascade effect, the contaminant can be transferred through different trophic levels within the food web, resulting in a cascade of negative effects on the reproduction, growth, nutrition, and even survival of the entire community (Batel et al., 2016; Cole et al., 2015; González-Soto et al., 2022; Lo & Chan, 2018; Murphy & Quinn, 2018).

Particularly in coastal areas that harbor coral reefs, tourism has been recognized as one of the main sectors related to direct ocean pollution by particulate matter from direct dumping and the particles from textiles such as swimwear, freediving, and scuba diving equipment, and cosmetic products (Arreola-Alarcón et al., 2022; Garcés-Ordóñez et al., 2020; Retama et al., 2016). Additionally, the indirect contribution of these pollutants from precipitation and continental runoff must be considered (Chubarenko et al., 2018; Pelamatti et al., 2019; Rios-Mendoza et al., 2021). Hermatypic corals are also susceptible to the presence of MPs as their ingestion may increase their bleaching susceptibility, cause tissue necrosis (Reichert et al., 2018; Syakti et al., 2019) and even create tissue lesions through mechanical abrasion, which besides the energy that the coral uses to produce mucus, it also cause physical damage to the organism, can act as a vector for the infection of bacteria and opportunistic pathogens (Corinaldesi et al., 2021; Page & Willis, 2008). This has led to a sense of urgency in determining the dangers that MPs can pose to marine ecosystems (Thompson et al., 2009), especially considering their ability to accumulate in various inorganic substrates such as water and sediment, as well as in biotic substrates such as algae and animals (Lozano-Hernandez et al., 2024; Saraswati, 2023; Soursou et al., 2023).

Coral reefs are currently recognized as highly vulnerable and threatened ecosystems, primarily due to the impacts of climate change (Hoegh-Guldberg, 2011). This is more alarming with the addition of other stressors, including the influence of continental waste, excessive visitor numbers, and poor tourism practices, which increase the potential negative effects on both corals and associated organisms (Lamb et al., 2018). Despite being a global concern, the presence of microplastics in coral reef ecosystems has reached alarming levels, even within Natural Protected Areas (Arreola-Alarcón et al., 2022), since the transport and dispersion of plastic debris transcend management or protection boundaries. Therefore, although coral reef sites located near urban centers are more highly exposed to these contaminants, their presence cannot be ruled out even in sites with low levels of human impact, where accumulation may slowly occur by indirect sources, but it will intensify as coastal urban development increases.

Characterizing the presence and abundance of potential microplastic (pMPs) particles in sediments is fundamental as a first step toward assessing the extent of contamination and elucidating their potential ecological consequences. The present study evaluates the abundance and type of pMPs in sediments from one insular Natural Protected Area and one coastal coralline site with no protection status but with low human-activity impact, both located in the Central Mexican Pacific. Such information contributes to the development of evidence-based management and conservation strategies, including initiatives for coral restoration. These approaches play a critical role in safeguarding marine biodiversity and maintaining the resilience and sustainability of the ecosystem services provided by coral reefs, which are vital to the well-being of coastal communities and the regional economy.

MATERIALS AND METHODS

Study site: A total of three sample sites were considered (Fig. 1). Two were located within the Islas Marietas National Park (IMNP), which is categorized as a Natural Protected Area (PNA) and has a coral restoration program implemented during the last ten years: Playa del Amor, an area with high visitation levels, and the Zona de Restauracion, a restricted-use site (Burroughs & Rodríguez-Troncoso, 2024). IMNP is an important conservation, migratory, and stepping-stone area for birds, mammals, fish, and invertebrates (Ortega et al., 2013). Additionally, it is a tourist attraction, and the management plan allows for visitation, with free diving and scuba diving being the most common activities (Cupul-Magaña & Rodríguez-Troncoso, 2017). Additionally, IMNP is located 6 km from Punta de Mita, one of the coastal communities with major tourist development in the Central Mexican Pacific, characterized by a rising urban development of high-end resorts, residences, and golf courses (Martínez-Castillo et al., 2020; Olivares González & Córdova-Martínez, 2022). In addition, the area is directly influenced by the Ameca and Pitillal rivers,

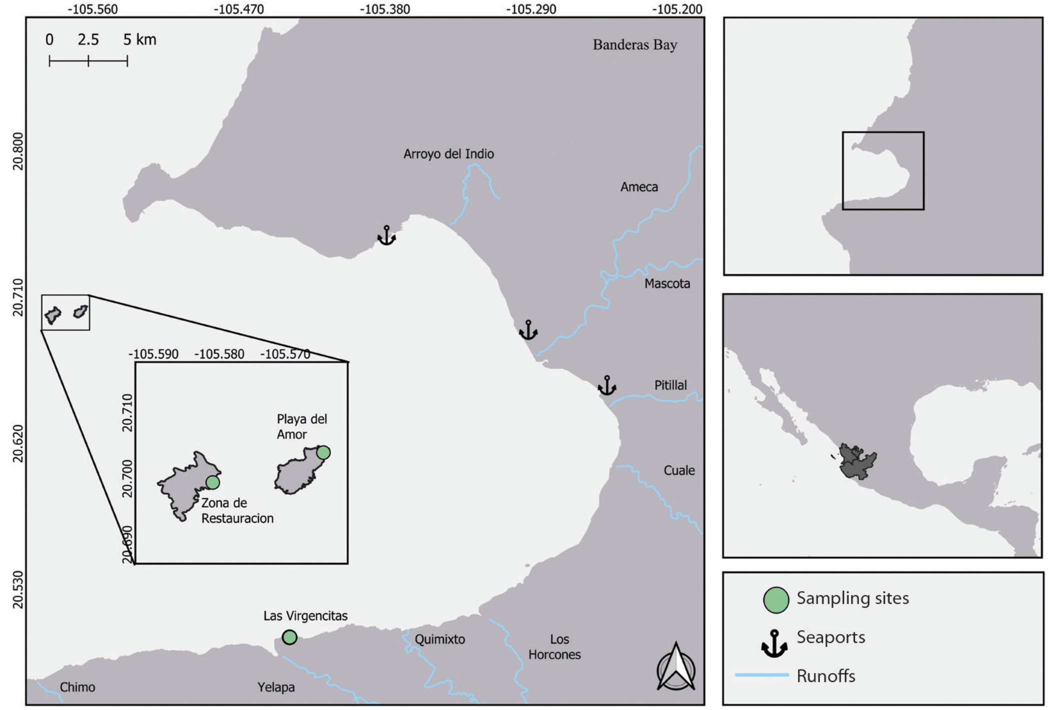

Fig. 1. Collection sites within Banderas Bay: Playa del Amor and the Zona de Restauracion in Islas Marietas National Park, and Las Virgencitas. The map marks the three sampling sites as well as the main seaports and runoffs in the area.

with an average annual runoff of 316.06 hm^3 (Morales-Domínguez et al., 2023), and only the Ameca river can allocate up to ≥ 70 % of the environmental water reserve during the rainy season (Salinas-Rodríguez et al., 2021).

The third sampled site was Las Virgencitas (LV, 20°30'03.8" N, 105°26'19.9" W), is located 30 km from IMPN and 2 km away from the nearest urban settlement (Fig. 1). This site is considered to have a low impact, where activities such as artisanal fishing and visitors who are primarily scuba divers visit the area. LV harbors a rocky reef at depths of 5 to 25 m that supports a high biodiversity of fish and invertebrates (Hermosillo-Núñez et al., 2023). This part of the bay is a central valley surrounded by the Cacoma and El Tuito mountain ranges, which act as natural hydrological boundaries, partially draining precipitation; however, there are small river systems that seasonally contribute with sediments, nutrients, and potentially polluting sediments and particles to the site (Velázquez-Ruiz et al., 2022).

Prevention of external contamination: To prevent contamination of the samples during handling, several quality control measures were implemented following the recommendations of Alonso Hernández et al. (2024). Cotton lab coats and nitrile gloves were worn during sample analysis, and hands were washed frequently to avoid contamination. Throughout the process, the use of plastic materials was avoided to prevent contamination from released particles. All glassware and metal tools were washed with tap water and detergent containing surfactants and bactericidal agents, followed by a thorough rinse with filtered distilled water to remove any remaining particles. After washing and decontamination, glassware and aluminum foil were burned at 550 °C for 5 hrs. Whatman (90 µm pore size, 70 mm diameter) glass fiber filters were individually inspected under a stereomicroscope prior to use to identify the presence of any particles. To reduce the risk of contamination from airborne laboratory particles, all samples were processed and analyzed inside a fume hood with the airflow off. Finally, as a complementary contamination control measure, at least one blank of CO_2-free distilled water was prepared, previously filtered, and placed in petri dishes during each phase of sample analysis (sediment drying, density separation, and particle separation in the stereoscopic microscope), which were only exposed during sample handling.

Sample collection and processing: Marine sediment samples were collected during the dry season (November 2025) via scuba diving at the three sites. For each collection, a 10 x 10 cm quadrant was used to delimit the surface area for sediment extraction. Within this quadrant, sediment was extracted to a depth of 5 cm, yielding approximately 500 cm^3 (Martin et al., 2017). To facilitate collection, four glass jars were used per quadrant, each with a capacity of 120 mL and a height of 6 cm. To prevent sample loss when removing the jars from the sediment, a bamboo scoop was used to cover the exposed part of the jar. Three replicates (quadrants) were sampled at each site, yielding 12 glass jars of marine sediment per site. The samples were stored in a cooler and transported to the laboratory, where they were stored at 4°C until further processing.

Initially, the total weight of each sample was obtained using a triple-beam balance. Subsequently, to remove excess water and material outside the MP range (>5 mm), the sediment was sieved using two mesh sizes, 5 mm and 1 mm, as recommended by Gárces-Ordoñez et al. (2020). The remaining moisture was removed by drying the samples for 24 consecutive hours at 50°C in a PRECISION 25EG oven to obtain the final dry weight (g). To avoid contamination, the samples were always covered with aluminum foil that had been burned.

The extraction of potential microplastic particles (pMPs) from sediment was performed using the density-shift technique (Bosker et al., 2018). To facilitate processing, sediment samples were divided into 50 g fractions, to which 200 mL of saturated $NaCl^-$ solution (1.2 g cm^{-3}), and a drop of biodegradable surfactant detergent were added to prevent the sediment from sticking to the container walls (Alonso Hernández et al., 2024; Bosker et al., 2018). It is important to note that the methodology used in this study is limited to the extraction of low-density plastics, since $NaCl^-$ has a maximum density of 1 200 kg m^{-3}, which is insufficient to extract higher-density MPs (Soursou et al., 2023). After extracting the low-density plastics, the samples were mixed with a metal stirrer for 2 consecutive minutes, then covered with burned aluminum foil, and allowed to stand at room temperature for 8 hours. The supernatant was transferred using a glass pipette and filtered through a Whatman glass filter (90 µm pore size, 70 mm diameter). Afterwards, the filter was placed in a clean petri dish, and the sample was digested by adding 1 ml of 10 % HCl to each one to remove hard residues such as $CaCO_3$ fragments. The filters (in the same petri dish) were individually dried at room temperature for 24 hours and covered with previously burned aluminum foil.

The potential microplastic particles were separated by shape and classified as described by Markley et al. (2024), using a ZEISS Stemi 508 stereomicroscope. The visible light spectrum was used to define and delimit the color classification, with violet and cyan included in the blue category, orange in the red category, and white, black, and transparent also considered. The pMPs found were photographed and classified by shape (fiber, fragment, sponge, film, and fiber bundle), color, and size (µm). Abundance was determined from the number of potential microplastics per gram of dry weight (pMPs/g dry weight).

Statistical analysis: A one-way analysis of variance (ANOVA) and Multiple pairwise comparisons using Tukey's test ($\alpha = 0.05$) were performed to identify differences in pMPs abundance between sites. Additionally, to determine differences in potential MPs' abundance by site and shape, a Friedman repeated-measures analysis of ranks was performed ($\alpha = 0.05$), with a posteriori Tukey's test ($\alpha = 0.05$). All results are expressed as mean ± standard deviation ($\overline{x} \pm SD$). Statistical analyses were performed using Sigmaplot V. 12.5 software (SigmaPlot, 2013).

RESULTS

The results show that in Playa del Amor, a total of 586 pMPs were extracted, with a relative abundance of 0.58 pMPs / g dw (dry weight). At the Zona de Restauracion, a total of 102 pMPs were registered, with a relative abundance of 0.10 pMPs / g dw. Finally, in the site Las Virgencitas, only 29 pMPs were extracted, resulting in a relative abundance of 0.029 pMPs / g dw. Statistical analysis revealed differences in pMPs abundance among the evaluated sites ($H = 6.48$, $p < 0.05$), specifically between the site with the highest abundance (Playa del Amor) and the lowest abundance, Las Virgencitas ($p < 0.05$).

Five pMP shapes were identified: fibers, fragments, foam, films, and fiber bundles (Fig. 2). The sediments from Playa del Amor accumulated mostly fibers (94 %), fragments (4 %), and 2 % composed of fiber bundles and foam. The samples collected in Zona de Restauracion also showed a high proportion of fibers (93 %), as well as some fragments and fibrous aggregates. At Las Virgencitas, all the pMPs were classified as fibers (Fig. 3). Differences in the forms present between sites were evident ($\chi^2 = 14.72$, $p < 0.05$), as foam and films were only recorded at Playa del Amor, and fiber bundles were only extracted from sediments in Zona de Restauracion.

Considering the size of the particles, the results shows that Playa del Amor pMPs ranged from 8.67 µm to 411 µm ($\overline{x} = 85.86 \pm 80.32$ µm), where the larger particles are represented by the fibers (112.98 ± 89.31 µm), and the films (101.49 ± 18.13 µm); meanwhile the fragments (35.49 ± 34.29 µm) and foam (30.22 ± 9.31 µm) have a smaller size particle. The pMPs found in the Zona de Restauracion had a minimum of 8.8 µm and a maximum size of 519.62 µm ($\overline{x} = 188.69 \pm 153.43$ µm), where the fibers were recorded as the particles with the major size of 225.36 ± 147.98 µm, followed by the fiber boundles 67.5 ± 7.80 µm and the fragments 12.82 ± 4.98 µm. The fibers recorded in

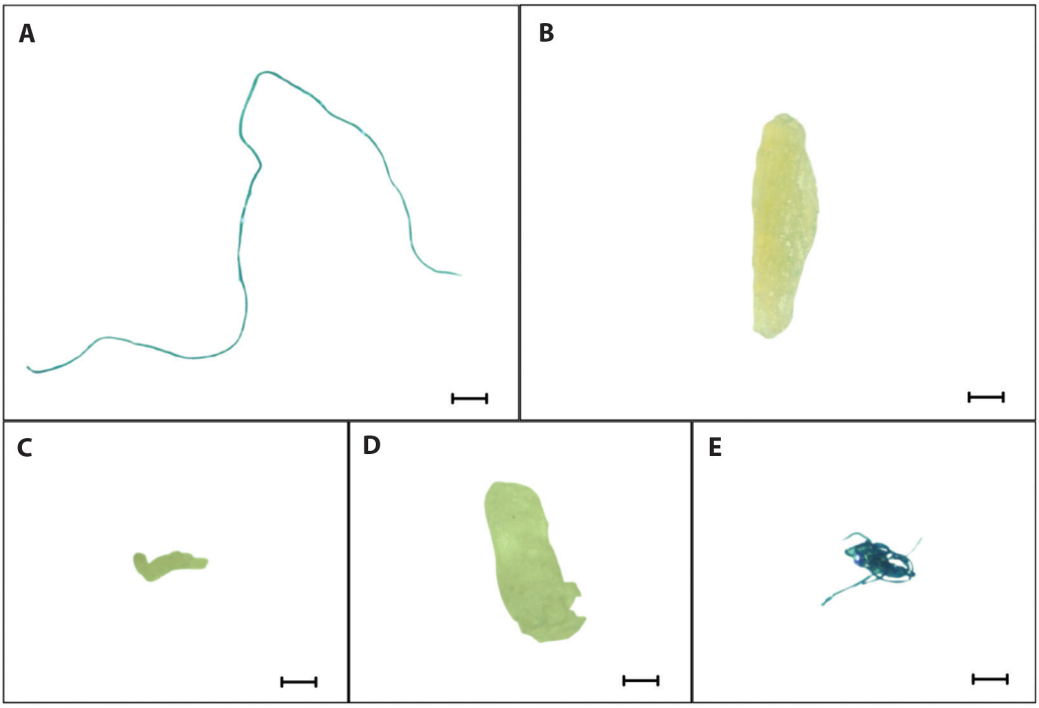

Fig. 2. Types of MPs shapes extracted in the sediment: **a)** fiber, **b)** fragment, **c)** film, **d)** foam, and **e)** fiber bundle. Scale bar size: 20 µm.

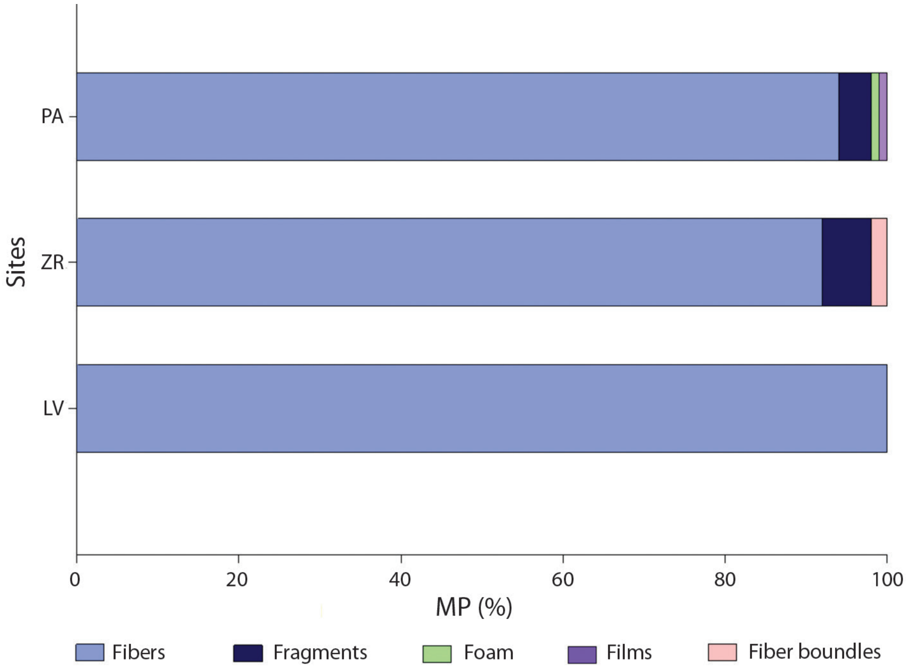

Fig. 3. Classification and relative abundance of the potential particles pMPs extracted from the sediments of Playa del Amor (PA), the Zona de Restauracion (ZR), and Las Virgencitas (LV).

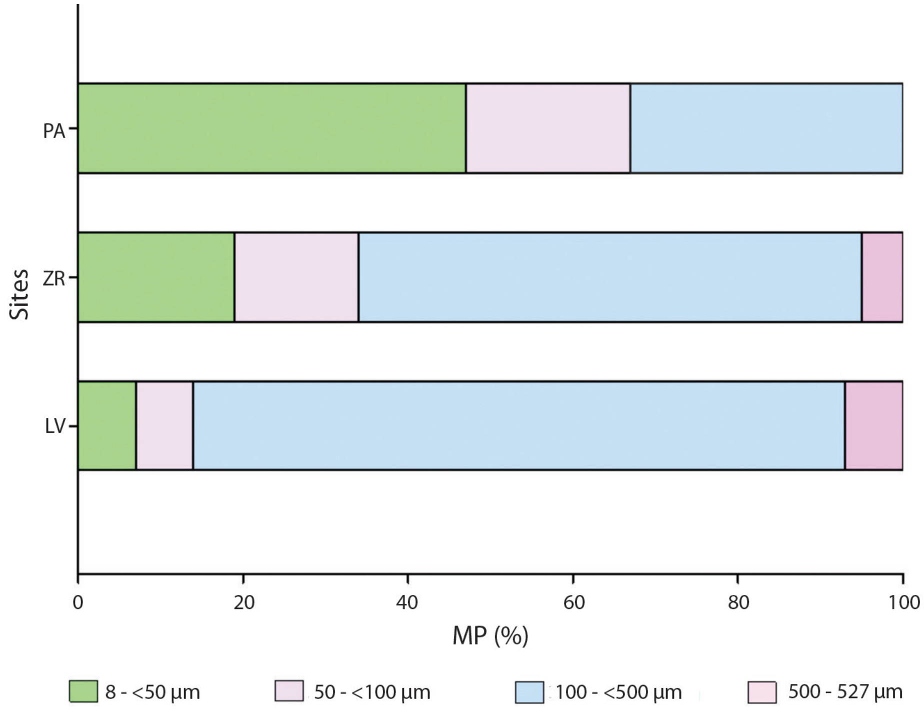

Fig. 4. Relative abundance of pMPs found in Playa del Amor (PA), Zona de Restauracion (ZR), and Las Virgencitas (LV), classified by size.

Las Virgencitas, as at other sites, exhibited high variability in size, with a mean of 188.69 ± 94.81 µm (Fig. 4).

Finally, the pMPs were also classified and separated by colour. For PA, most particles were yellow (192), blue (172), and black (104). For the ZR yellow (13 particles). In LV, the most represented colors were blue (17 particles) and black (6 particles). Other colors were also identified, including white in Playa del Amor and red, green, and colorless in all three sites (Fig. 5).

DISCUSSION

The results provide the first evidence of possible accumulation of pMPs within coralline habitats exposed to differential levels of direct and indirect plastic sources in the Central Mexican Pacific. The presence and abundance of pMPs in marine systems have been linked to anthropogenic activities, particularly tourism and recreational activities (Mauludy et al., 2019; Sundar et al., 2021; Yu et al., 2016), and even a pattern of an increase of up to 10% of their abundance and size (at least 2-fold length) has been documented before and after the high tourist seasons (Gül, 2023). This similar pattern can be observed in non-commercial areas where human intervention is minimal resulting in averages below 60 pieces per kg-sand, meanwhile commercial beaches compared with a range of 100 to 300 pieces per kg-sand (Yu et al., 2016). While this is a global phenomenon, the presence of MPs has reached alarming levels even in coastal NPA´s such as Bahías de Huatulco National Park, which is exhibiting high accumulation rates, doubling within a mere two-year period which have been directly linked to local tourism-recreational activities and poorly managed waste from the surrounding hotel infrastructure (Retama et al., 2016).

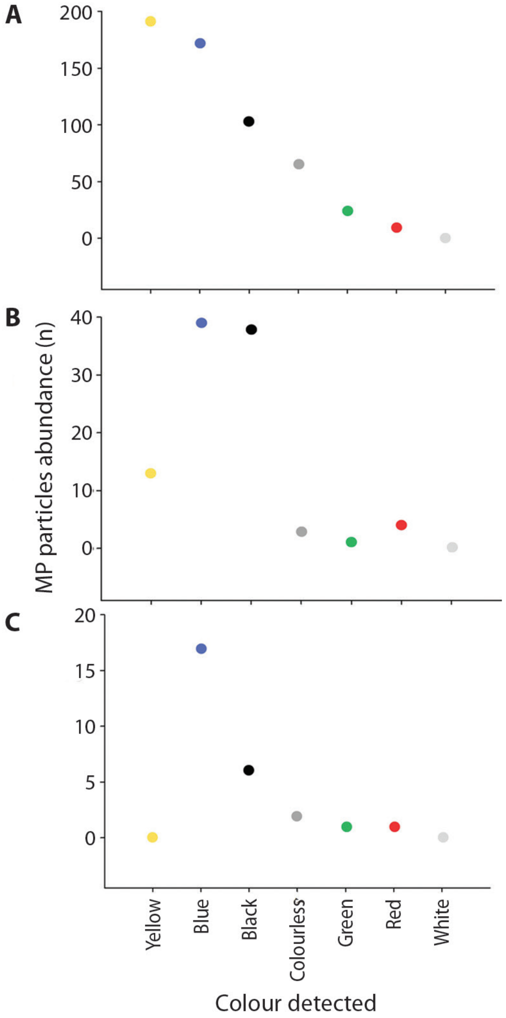

Fig. 5. Abundances of the pMPs classified by color in the three sampling sites: **a)** Playa del Amor, **b)** Zona de Restauracion, and **c)** Las Virgencitas.

Our results showed that Playa del Amor exhibited an accumulation of particles approximately 5 times higher than the Zona de Restauracion, which has a distance of ≈ 3 km, and also within the limits of the NPA, but it is a restricted-use area (Comisión Nacional de Áreas Naturales Protegida [CONANP], 2007). Although neither site is directly connected to tourist or urban development, daily tourist activities can occur in the area, especially Playa del Amor, which is considered a tourist hotspot. Ten years ago, uncontrolled visitation to the area (up to 30 000 tourists per year) led to a three-month closure of the NPA (Burroughs & Rodríguez-Troncoso, 2024), followed by the implementation of a carrying capacity program, with a regulated visitation that now cannot reach over 10 000 tourists per year (Cupul-Magaña & Rodríguez-Troncoso, 2017). Although this regulation has already been implemented, the historical high visitation has been a direct contributor to the presence of pMPs in the area.

However, it should also be considered that the presence of microplastics is the result of multiple anthropogenic sources and processes, rather than a single point of origin. Therefore, indirect sources, such as the terrestrial runoffs that discharge in nearby areas, as well as wind and currents, transport particles into the ocean (Asensio-Montesinos et al., 2022; Retama et al., 2016; Ríos-Mendoza et al., 2021; Thompson et al., 2004). As a result, sites that should have low levels of human impact remain vulnerable to the accumulation of contaminant particles, as it was recorded in Zona de Restauracion site, which shows evidence of stored plastic particles, despite this being a restricted area (CONANP, 2007), with a special protection rules and particular implementation of conservation efforts such as the implementation of a coral restoration program (Tortolero-Langarica et al., 2019). Islas Marietas National Park is situated 8 km from Punta de Mita, a high-end tourist development featuring hotels, urbanization, and golf courses (Martínez-Castillo et al., 2020), which could be considered an important contributor of contaminants (not only microplastics particles) but not the only one, since also on the same island is the Cueva del Muerto site which is also highly visited and used mainly for snorkeling (Burroughs & Rodríguez-Troncoso, 2024), and is also only 2 km away from Playa del Amor (CONANP, 2007), both being vectors that can contribute to the input of particles in the Zona de Restauracion site. This is also the case of Las Virgencitas, which, despite the low visitation, is still impacted by the direct and indirect anthropogenic pressure, and most of the particles may reach the site by the rivers' input (2 km away) and the small seasonal runoffs that influence the area all year long, particularly during the rainy season (Arreola-Alarcón et al., 2022; Asensio-Montesinos et al., 2022; Li et al., 2020). Particularly, the Ameca river has a significant annual runoff that influences the area equivalent to 23 % (in the dry season) up to 73 % (along the rainy season) of the environmental water reserve in the Mexican Pacific (Morales-Domínguez et al., 2023; Salinas-Rodríguez et al., 2021), which also means that it carries particles along the river course, which eventually will be discharged as urban waste, representing up to 80 % of the plastic pollution that enters the oceans (Álvarez-Zeferino et al., 2020).

The shapes of pMPs recorded in IMNP include fibers, fragments, foam, and films in Playa del Amor and fibers, fragments, and fiber bundles in Area de Restauracion; but in both sites, fibers were the most abundant form (90 %), while at Las Virgencitas, fibers represented all the particles. The different shapes of pMPs are derived from their source, and so far, fibers are considered the most abundant in marine sediments (Balestra & Bellopede, 2022; Martin et al., 2017). These MPs can be considered of both primary and secondary origin, as they can detached and wear of items such as swimsuits commonly used in water sports, from fishing nets and ropes left in the ocean and exposed to the marine environment, as well as from the abrasion during the washing of synthetic textiles (Arreola-Alarcón et al., 2022; Boucher & Friot, 2017; Negrete Velasco et al., 2020; Tigua Zambrano & Pardo Reyes, 2024), even generating groups of microfibers that appear as fibers bundles (Yang et al., 2023). Therefore, the variability in the distribution of plastic forms is related to local or direct sources, that is, those originating from on-site activities, such as tourism and recreation (Luo et al., 2022). Plastic fragments were the second most abundant. Their origin is related to the breakage of larger plastics, such as cleaning products and plastic utensils, among others. Within this category, other forms can also be classified, such as films, considered soft fragments that can detach from packaging, plastic bags, containers, and wrapping paper (Álvarez-Zeferino et al., 2020; Oni et al., 2020); one particularity is that they have low abundance because the fragmentation and residence process can affect their shape, transforming it into filaments (Chubarenko et al., 2018; Oni et al., 2020). Foams are also considered secondary sources of plastic pollution (Zhao et al., 2021), as they result from the breakage, detachment, and fragmentation of larger plastic products, such as disposable cups and plates which have as a main component expanded polystyrene (Álvarez-Zeferino et al., 2020; Markley et al., 2024).

In addition to abundance and shape, the size of plastic particles is also an important indicator. The data showed that both the widest and the smallest size ranges were recorded in IMNP sites. It has been previously documented that particulate matter tends to fragment gradually due to sunlight, water movement, microbial activity, and other factors (Flores-Cortés & Armstrong-Altrin, 2022; Lobelle & Cunliffe, 2011). Therefore, the size difference between sites may be a result of the residence time and the level of exposure to these environmental factors, which together influence the rate of particle degradation (Cai et al., 2018). The smaller size of pMPs recorded in Playa del Amor and also in Las Virgencitas may indicate a longer residence time compared to particles from the Zona de Restauracion, suggesting that pMPs deposition at this site is more recent (Sulistiowati et al., 2023).

Finally, color, like shape, may provide information to determine the origin of the plastic particles (Kim et al., 2023). The most abundant colors observed were blue and black, with yellow also present at Playa del Amor. Black pMPs may originate from cables, containers, and tires (Kim et al., 2023); while blue particles are primarily associated with the textile industry, which uses indigo dye to color fabrics (Godoy et al., 2022). Yellow-colored particulate matter can originate from the oxidation and/or photodegradation of various plastics, including polyvinyl chloride (PVC), which is a material commonly used in construction products such as hoses, cables, waterproofing materials, pipes, and upholstery, and all of them, releases hydrogen chloride when exposed to sunlight, causing a yellowish discoloration (Issac & Kandasubramanian, 2021). Given the high diversity of potential sources contributing to plastic particles of different colors, associating a specific color with a particular source at each site is not appropriate. Nevertheless, the very low abundance of white or transparent particles in the restoration area is noteworthy, especially considering that the direct propagation technique using fragments of opportunity has relied mostly on the use of plastic cable zip ties to stabilize and fix the coral colonies (Tortolero-Langarica et al., 2019). This may prove that the restoration-related materials used so far are not representing a major local source of microplastic inputs and highlights the relevance of the direct and indirect sources previously discussed, in shaping the observed particle composition.

Microplastics are now recognized as an emerging and increasing threat to marine biodiversity, despite evidence that these contaminants have been present in reef substrates for several decades. So far, the damage that these particles can cause to the coral population in our study area has not been characterized; however, the rising concentrations and the effects of other synergistic local and global stressors can undermine coral health, thereby increasing their susceptibility to bleaching and mortality (Reichert et al., 2018; Syakti et al., 2019) and increasing their vulnerability to other stressors (e.g. thermal stress) or even pathogens as their immune system can be compromised (Corinaldesi et al., 2021; Page & Willis, 2008). Current evidence shows that corals are experiencing sustained stress driven by global-scale processes, including increasingly intense and frequent thermal anomalies related to the El Niño Southern Oscillation events over the past four decades (Cai et al., 2023), which have resulted in mass mortalities across the Eastern Tropical Pacific (Romero-Torres et al., 2020) with differential ability to recover along the region (Alvarado et al., 2025; López-Pérez et al., 2024). In addition to the global pressures, local anthropogenic stressors have emerged as major vectors of disturbance, and this should be specially reviewed as the results showed that coral reef-related tourism is a major vector to introduce pMPs in, but at the same time, recently the touristic activities has been recognized as a major source of revenue with an annual global value of US$35–36 billions including direct activities like diving and snorkeling (“on-reef” tourism) and indirect such as beach tourism and coastal amenities also called “reef-adjacent” tourism (Spalding et al., 2017). With this current scenario it is urgent to promote different strategies to decrease the primary sources of plastic particles, as a necessary measure to counteract the increasing levels of these contaminants, reducing their potential impact and therefore the vulnerability not only of corals but also of other organisms within the whole coral community.

Ethical statement: The authors declare that they all agree with this publication and made significant contributions; that there is no conflict of interest of any kind; and that we followed all pertinent ethical and legal procedures and requirements. All financial sources are fully and clearly stated in the acknowledgments section. A signed document has been filed in the journal archives.

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