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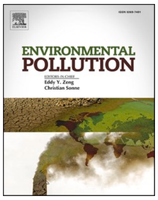

Review

Do coral reefs act as sinks for microplastics?☆

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ABSTRACT

Microplastic (MP) pollution has been detected in coral reefs, raising concerns regarding its global impact. Although they cover a small portion (<1%) of the total area of the world's oceans, coral reefs are geological and biological structures that trap MPs and disproportionately enhance their accumulation. In this review, we attempted to understand how coral reefs act as short- and long-term sinks for MPs. We describe five characteristics that lead to the enrichment of microplastics in coral reefs: 1) adhesion on reef-building corals at distinct depths; 2) ingestion by reef organisms (e.g., suspension feeders, such as sponges, ascidians, and corals), bioconcentration, and formation of short-term (i.e., years to decades) biological sinks for MPs; 3) formation of long-term (i.e., centuries) MP sinks in coral skeletons and unconsolidated subsurface sediments; 4) reduction of sediment resuspension and seafloor turbulent kinetic energy by complex marine forest architecture that reduces bottom shear stress, facilitates the retention, and deposition of small (<0.5 mm) and high-density floating MPs; and 5) diagenesis of Anthropocene sedimentary rocks containing MPs. We estimate that reef processes may remove more than 10% of floating MPs in shallow tropical waters yearly. Statistical results show that microplastic abundance for reef-building corals are higher than values found in reef sediments and especially in seawater. Moreover, pellets, films, foams and mainly fragments and fibers have been found. These field-based data support our hypothesis of sinks in the reef sediments and organisms. We highlight the role of these seascapes in the interception of MPs as traps and sinks in reef sediments, biota, and carbonate frameworks. As coral reefs are prone to MP accumulation and can become pollution hotspots, global initiatives are necessary to conserve these rich ecosystems and prevent rapidly increasing plastic pollution.

1. Introduction

Microplastics (MPs) have become a global concern due to their persistence in many habitats worldwide, including in coral reefs (Lartaud et al., 2020; Soares et al., 2020). Research on MP pollution in coral reefs has increased in recent years because of the widespread presence of large plastic litter that degrades to smaller-sized particles known as secondary MPs (Frias and Nash, 2018). In addition, primary MPs can be found worldwide because of mismanagement (Reichert et al., 2018; Akdogan and Guven, 2019). Nanoplastics (from 100 nm to 1 μm, (Piccardo et al., 2020; International Organization for Standardization, 2020), which represent a threat to reef organisms and require further investigations, are even more difficult to detect and quantify (Gopinath et al., 2020).

Coral reefs have a high potential to become coastal pollution hotspots because of their capacity for interception of particles, complex ecosystem structure (Soares et al., 2020), burial in reef sediments (Utami et al., 2021), and their location in sheltered nearshore environments,

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such as coastal bays and lagoons, where microplastics can be transported from the mainland or by tides and waves (Arreola-Alarcón et al., 2022). This is of particular concern, considering that foundation organisms and their complex habitats are potential sinks for MPs worldwide (Martin et al., 2019; Corona et al., 2020) Surprisingly, MPs smaller than 1 mm are absent from surface waters worldwide (Browne, 2015), pointing to the presence of extensive MP sinks, such as coral reefs, on the seafloor. To confirm this hypothesis more research is required, such as we proposed here.

Several articles have recently been published on the occurrence, sources, and impacts of MPs in coral reefs (Soares et al., 2020; Huang et al., 2021); however, no review has attempted to understand why MPs are present in coral reefs at relatively high concentrations. Overall, we found that published research has focused mainly on the occurrence, sources, and impacts of MPs in coral reefs while ignoring the role of these seascapes in the interception of MPs as traps and sinks in reef sediments, biota, and carbonate frameworks. As coral reefs are prone to MP accumulation and can become pollution hotspots, global initiatives are necessary to conserve these rich ecosystems and prevent rapidly increasing plastic pollution. Therefore, our research attempted to understand how coral reefs act as both short- and long-term sinks for MPs. This review aims to present a comprehensive summary and discussion of the current knowledge on the role of coral reefs as traps and potential sinks for MPs.

2. Methods

A review of the available literature was conducted to extract quantitative and qualitative information from published papers on microplastic enrichment in coral reefs (seawater, sediments, and reef-building corals). First, objectives and questions were defined. Next, terminologies were pre-screened to ensure that the search terms and strings used in the database queries aligned with the most prevalent scientific terms used to describe microplastics and coral reefs. Following the literature search of databases (Web of Science, Scopus, Google Scholar, and SciELO), the manuscript selection workflow was based on the protocol of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). We follow the items proposed by the PRISMA method (checklist items 1–27 in Tam et al., 2017).

The objective of this study was to investigate the current state of knowledge regarding the drivers of MP accumulation in coral reef habitats. The following research question guided our review: 1. What are the main characteristics of these field-based studies (e.g., reef compartments such as seawater, sediments, and coral species)? In this review, we did not focus on the impacts and occurrence of microplastics on corals or on experimental and laboratory studies.

Qualitative and quantitative analyses of the published literature were performed in two stages following methodology for reviews. First, the terms "microplastics," "coral reefs" AND/OR "corals," "reef sediments," "tropical reefs," "shallow-water reefs," and "reef-building corals" were searched in online search engines. The search was limited to titles, keywords, and/or abstracts of the evaluated papers according to the bibliographic database. Timescale boundaries were imposed on the papers, i.e., published until January 2023. The search included only studies published in peer-reviewed scientific journals. Gray literature, laboratory (or aquaria studies), extended abstracts, congress presentations, official technical reports, book chapters, and non-English papers were excluded. We have detected 98 bibliographic references, but most of them are from laboratory or aquarium experiments. Thirty-one (31) articles that provided field-based information from the selected articles were identified. The extracted data from field-based research were exported to a spreadsheet according to a predetermined set of attributes, and the results were obtained.

To identify any articles overlooked during the first selection step, we consulted references cited in recent reviews (Soares et al., 2020; Huang et al., 2020). All papers with English titles and abstracts were manually screened for content, and the selected papers were downloaded and examined individually (98 articles).

Thirty one published peer-reviewed articles (2019–2023) met our established criteria and addressed the mechanisms and field-based data on the retention and contamination of microplastics in coral reefs. Based on these 31 articles, we extracted information about the reef location, country, plastic types, and type of sampled compartment (water, sediment, or coral) to obtain a data review. With this information we produced 3 graphs (using datawrapper) showing the range for the 1) abundance of microplastics, 2) the size ratio of microplastics and 3) types of microplastic polymers found in water, reef sediments and tropical reef building corals. Moreover, we used VOSviewer 1.6.19 to visualize and analyze trends in the form of bibliometric maps of the microplastics and coral reefs. We used open-access software for data mining, mapping, and grouping topics obtained from the Web of Science database (2010–2023) (van Eck and Waltman, 2009). For the VOSviewer analysis, a minimum threshold of 10 relationships was considered.

3. Coral reefs studies: focus on the impacts with a bias sampling

MPs are being increasingly reported in onshore and offshore tropical reefs, with potential sources identified as riverine inputs from coastal cities, shipping, and local fisheries (Critchell et al., 2019; Huang et al., 2019; Jensen et al., 2019). Human activities, such as tourism, urbanization, and nautical and fishing activities, have been linked to MP contamination in different reef compartments (water, sediments, and biota) (Arreola-Alarcón et al., 2022; Patterson et al., 2022; Zhou et al., 2023). In this context, our quantitative analysis of published research (n = 31 studies) (Supplementary Material 1) revealed that most studies (63%) focused on the microplastics in the seawater of reef ecosystems, followed by sediments (50%), whereas only 30% of the studies assessed MPs in reef-building corals themselves (Fig. 1).

Results (plot range) showed that microplastic abundance for reef-building corals are higher than values found in reef sediments and especially in seawater (Fig. 2). These field-based data support our hypothesis of sinks in the reef sediments and organisms. Moreover, pellets, films, foams and mainly fragments and fibers have been found (Fig. 3) in the reef compartments. Regarding the types of microplastics polymers, eight different types have been found, with CP (Cellulose propionate),

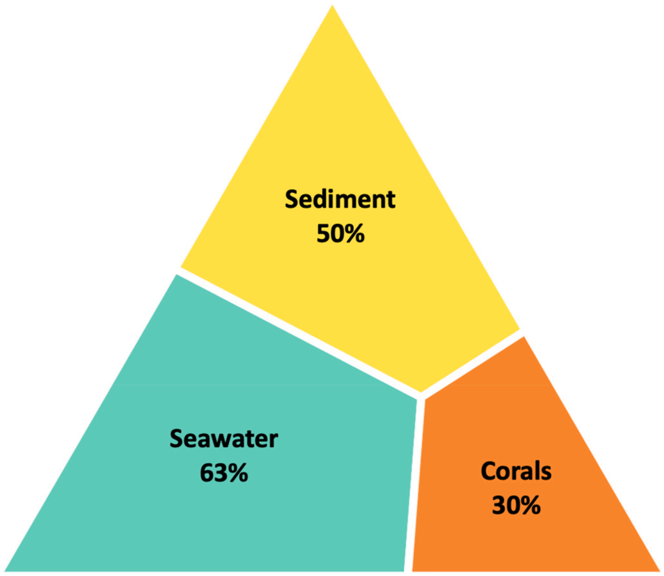

Fig. 1. Percentage of published papers (N = 31 studies) that analyzed microplastics in seawater (mainly studied compartment), reef sediments, and corals on tropical shallow-water reefs worldwide.

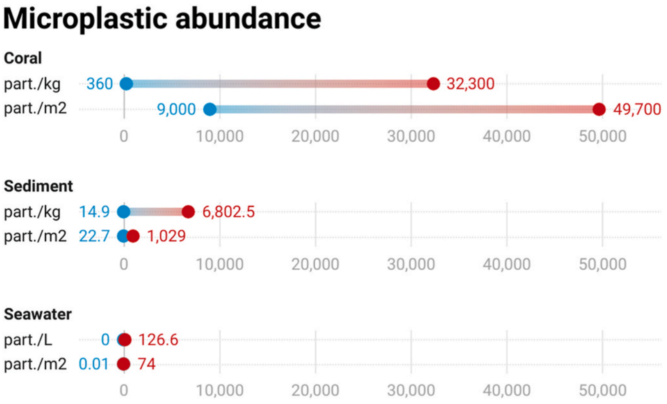

Fig. 2. Plot range (min – max) of microplastic abundance in reef-building corals, unconsolidated reef sediments and seawater based on published research (n = 31 studies). Figure created with Datawrapper.

PE (polyethylene) and PA (Polyamide) reaching the highest levels in corals (Fig. 4). The microplastic profiles are differentiated according to the type of compartment which demonstrates different accumulation processes and presence.

Some research studies focus on more than one compartment (Supplementary Material). The geographic distribution of the studies (Fig. 5) shows the widespread presence of MPs in several reef regions worldwide. However, most studies have been conducted on reefs in Asia and have focused on MPs in seawater. In this regard, most of the studies are located in water from Asia and Oceania and few reefs were studied outside this area. It greatly limits the representativeness at worldwide scales because different environmental conditions can lead to different influences, for example in MPs trapping, coral growth rates, currents velocity and direction or the distance with an input source (e.g., urban areas).

In the keyword co-occurrence map, the bibliometric analysis indicated two interconnected clusters of research topics on the relationship between MPs and coral reefs (Fig. 6). The keywords "ingestion," "species," "effect," and "exposure" clustered together (in green color), suggesting a close relationship between them, mostly related to the impacts of MPs on the reef organisms. A second cluster (in red color—left side) includes the keywords "fiber," "polypropylene," "polyethylene," "occurrence," "sediment," "region," "distribution," "source," and "abundance". This cluster (Fig. 6) and meta-analysis (Fig. 4) showed the main types of MPs found (e.g., polypropylene and polyethylene) and the reef sediments regarding sources and regions.

4. Coral reefs: characteristics that lead to the accumulation of microplastics

Tropical marine ecosystems interlinked with coral reefs, such as mangroves (Wang et al., 2023) and seagrass beds (Huang et al., 2020), have higher MP concentrations than the surrounding unvegetated flat environments. This indicates that environments with more complex structures have a greater potential for accumulating MPs in tropical waters. In addition, mangrove and seagrass bed sediments are enriched with MPs owing to the interception and plastic particle trapping processes (Huang et al., 2020; Wang et al., 2023), potentially becoming MP pollution hotspots over the coming decades. Similar depositional

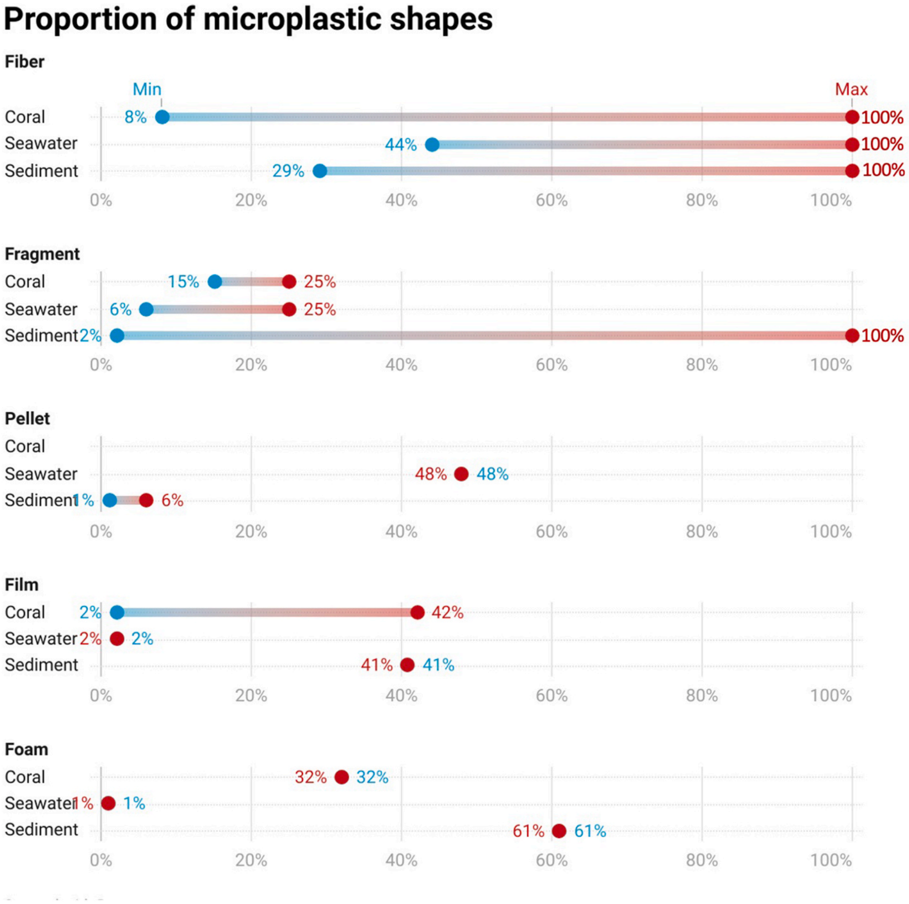

Fig. 3. Plot range (min – max) of relative abundance of microplastic shapes in reef-building corals, unconsolidated reef sediments and seawater based on published research (n = 31 studies). Figure created with Datawrapper.

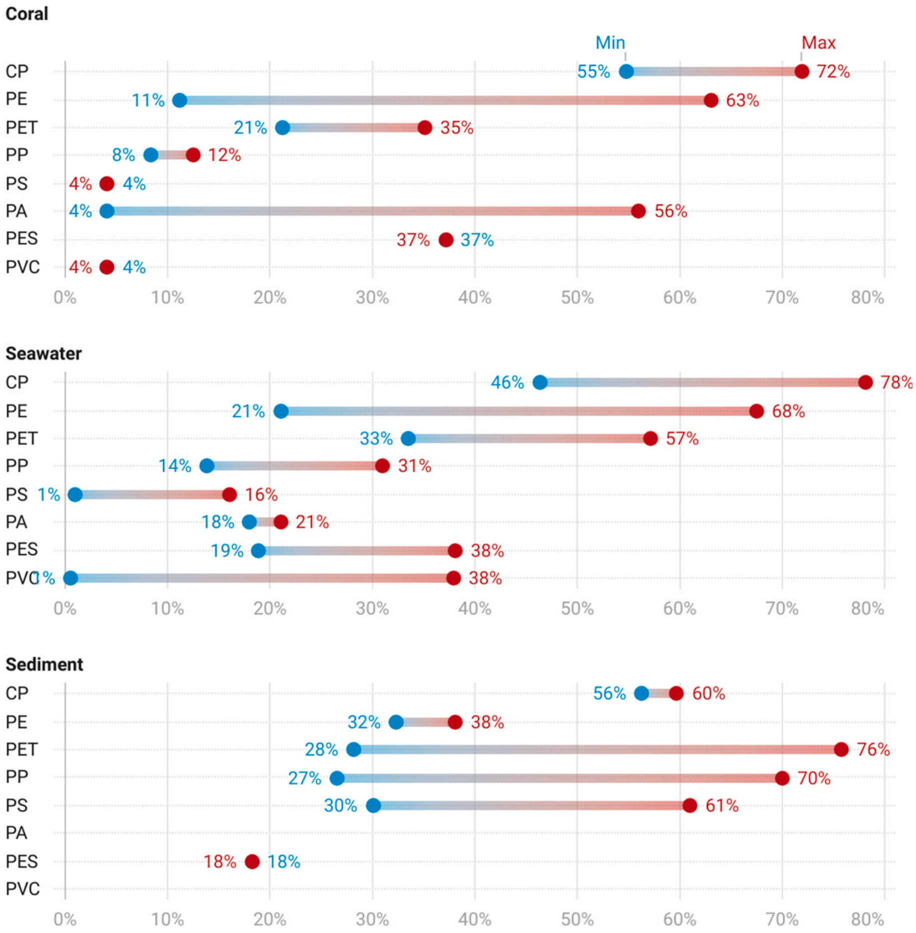

Fig. 4. Plot range (min – max) of relative abundance of microplastic polymer types in reef-building corals, unconsolidated reef sediments and seawater based on published research (n = 31 studies). Figure created with Datawrapper. Acronyms: Cellulose propionate (CP), Polyethylene (PE), Polyethylene terephthalate (PET), Polypropylene (PP), Polystyrene (PS), Polyamide (PA), Polyethersulfone (PES), Polyvinylchloride (PVC).

processes of accumulation and enrichment of MPs occur in coral reefs in both sediments (Béraud et al., 2022) and reef organisms (Hierl et al., 2021; Reichert et al., 2021; Tang et al., 2021; Hung et al., 2022; Lim et al., 2022).

The risk of MP accumulation (hotspots) in coral reefs is probably higher than that in mangrove and seagrass beds, given that recent studies have shown that, in addition to sediments, many coral species can also incorporate fibers and plastic particles (e.g., polyethylene terephthalate) into their biological tissues (Tang et al., 2021; Zhou et al., 2022) and carbonate skeletons (Hierl et al., 2021; Reichert et al., 2021).

Overall, coral reefs occupy less than 1% of the world's oceans and have several geological and biological structures that trap MPs and enhance plastic enrichment. In the following section, we describe five key characteristics that lead to the reef enrichment by plastic pollution: 1) adhesion on reef-building corals at distinct depths; 2) ingestion by reef organisms, such as benthic suspension feeders, trophic transfer, and formation of short-term (i.e., years to decades) biological sinks for MPs; 3) formation of long-term (i.e., centuries) MP sinks in coral skeletons and subsurface unconsolidated sediments; 4) the complex architecture that reduces bottom shear stress and hampers the sediment resuspension and seafloor turbulent kinetic energy, increasing retention and deposition of small, high-density sinking MPs; and 5) recent diagenesis in the Anthropocene of sedimentary rocks which form long-term MP sinks (Fig. 7).

5. Reef compartments as sinks for microplastics

5.1. Adhesion to corals and ingestion by reef organisms

High densities and complex ramifications of reef organisms (Rossi et al., 2022) can be crucial for retaining MPs, as particle retention is more effective in high-density patches, an approach adopted to increase prey capture rates (Rossi and Rizzo, 2021). MPs may passively affect corals by adhering to the external surface of the organism (Allen et al., 2017; Hankins et al., 2018; Martin et al., 2019; Procter et al., 2019), which is a key factor in accumulating plastics in reef ecosystems at both individual and colony scales. In a recent study of three species of coral in the Red Sea reefs, Martin et al. (2019) found that adhesion is 40 times more effective than ingestion for removing MPs from seawater. In another investigation of Maldivian coral reefs, adhesion was the main route of MP accumulation (8%) in *Danafungia scruposa,* whereas ingestion played a negligible role (≈2∼) (Corona et al., 2020). Recent studies have shown that even with different polyp sizes, morphologies, and coral biogeographic regions, adhesion is the major driver of MP accumulation in coral reefs, leading to short-term sinks that trap floating MPs transported by hydrodynamic forcing (Martin et al., 2019; Corona et al., 2020).

Mucus production by corals is a physiological response to multiple stress factors, such as exposure to low tide (Krupp, 1984), invertebrate larval settlement (Fearon and Cameron, 1996), and sediment deposition (Bythell and Wild, 2011). In addition, an increase in suspended particles in the surrounding water may also promote mucus production (Erftemeijer et al., 2012), and corals exposed to increasing amounts of MPs

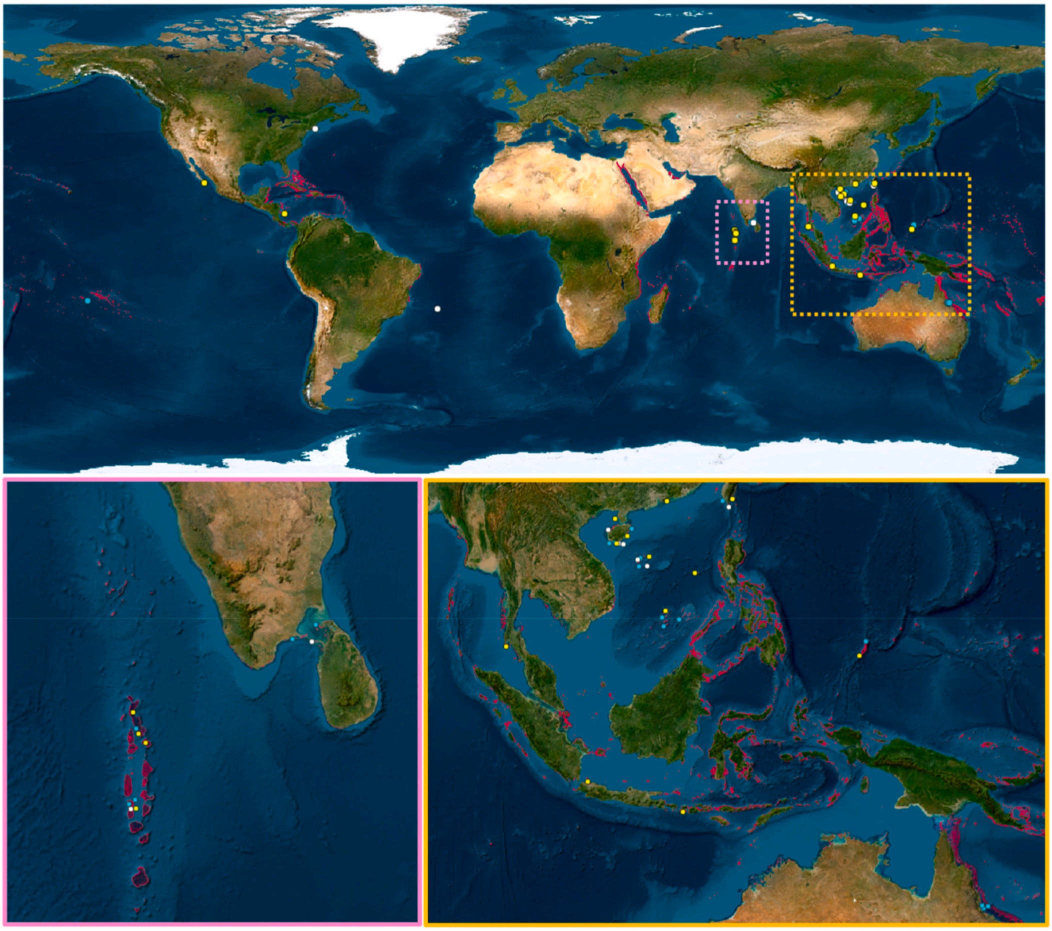

Fig. 5. Map showing global detection of microplastics in reef compartments such as reef seawater (blue dots), unconsolidated reef sediments (yellow dots), and reef-building corals (white dots) worldwide. The bottom insets provide a zoom-in view of the regions with higher number of studies. Coral reefs are outlined in red (Source: UNEP-WCMC: http://datda.unep-wcmc.org).

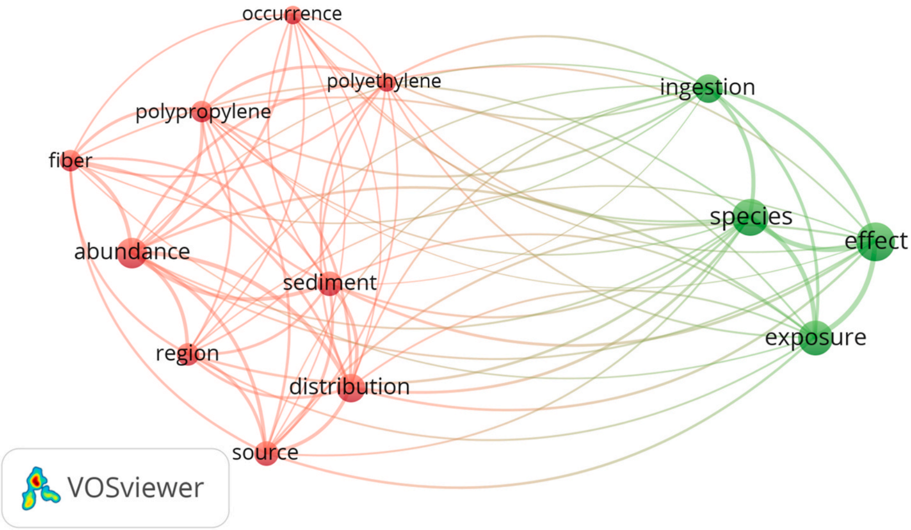

Fig. 6. Network of the co-occurrence of keywords on topics related to microplastics and coral reefs verified in the abstracts of the 31 studies identified in the present review, plotted in VOSviewer. The font and circle sizes representing each word is proportional to the frequency of its occurrence (larger circles represent topics cited more often in the abstracts of the papers).

show a higher rate of mucus production (Corinaldesi et al., 2021). Because of its viscous nature, this mucous layer facilitates the adhesion of microplastics which, in turn, stimulates further mucus production, reinforcing the role of adhesion as a mechanism of MP accumulation and transfer to skeletons in scleractinian corals on tropical reefs.

MP ingestion is another species-specific enrichment process derived

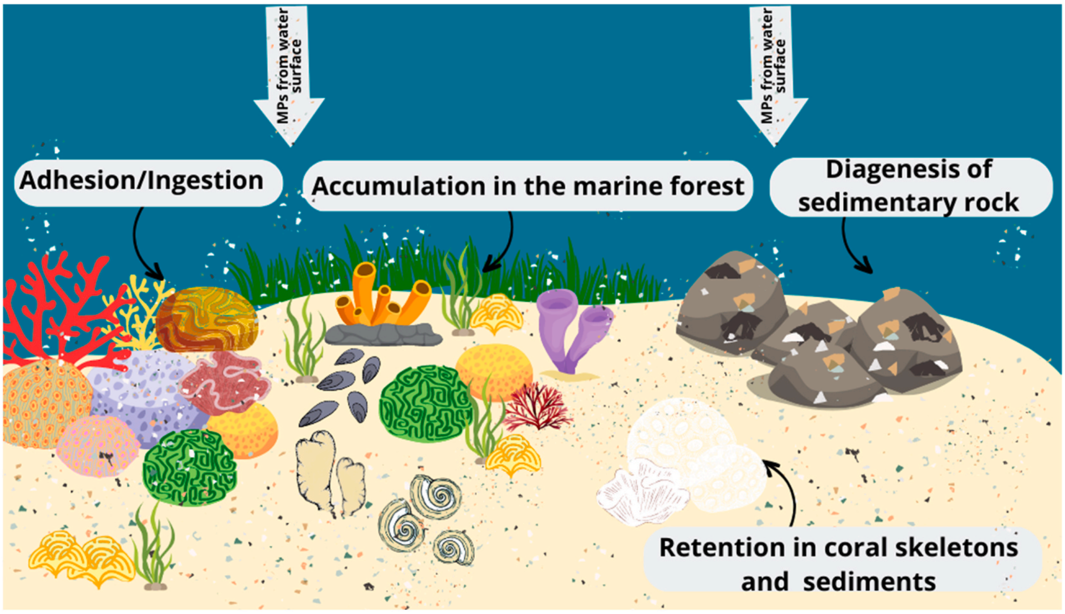

Fig. 7. Key processes that lead to microplastic enrichment in coral reefs, such as unconsolidated sediments and diagenesis of sedimentary rocks, and reef organisms. Source: the authors.

from the type of coral feeding mechanism, that is passive or active (Hall et al., 2015), as MPs may accumulate in coral tissues via direct ingestion (Hall et al., 2015). In other words, scleractinian corals may intercept and accumulate MPs from marine environments (Martin et al., 2019; Tang et al., 2021; Zhou et al., 2023), possibly through a species-specific pattern of ingestion and incorporation into tissues, with some corals having a greater potential for accumulation than others. Morphological and ecological traits, such as polyp size (Lei et al., 2021), heterotrophic plasticity (Zhou et al., 2023), and the interaction between calyx and microplastic size (Hankins et al., 2022), may affect accumulation potential (Zhou et al., 2022). In addition, environmental factors, such as water currents and seawater temperature, can affect polyp expansion and influence the ingestion rates of food (Rizzo et al., 2022; Rossi et al., 2019), including MPs. MPs may be captured, ingested, or partially or totally egested depending on the quantity and type of MPs, phagostimulants, and reef-building coral species (Hall et al., 2015; Allen et al., 2017; Hankins et al., 2018; Reichert et al., 2018; Montano et al., 2020).

Reef-building corals probably lack a selection mechanism that allows their polyps to distinguish particles found in the water, that is, zooplankton (i.e., food item) and MPs (Savinelli et al., 2020). Thus, corals can easily mistake MPs for their plankton prey and ingest them and plasticizer additives (Montano et al., 2020). Corals cannot distinguish MPs from their natural prey but may select MPs (Hall et al., 2015; Lartaud et al., 2020). In addition, MPs may also be translocated within polyps (Grillo et al., 2021), as they are found in the mesenteric coral tissue within the coral gut cavity (Rotjan et al., 2019; Lartaud et al., 2020). Selectivity is when the coral can make egestion by detecting that the material is microplastic (and not organic food). Non-selective is when there is no chemical differentiation between plastic particles and living organisms (or digestible organic matter).

In addition to corals, other suspension-feeding benthic organisms are widespread and abundant in tropical reefs. Owing to their filtration feeding in the water column (Fraissinet et al., 2023), these organisms have also been found to be contaminated by MPs (Aranda et al., 2022; Soares et al., 2022) and contribute to accumulating these pollutants in coral reefs. Among these, bivalves are widely used as indicators of the presence of MPs in reef environments and are potential temporarily stocking of MPs (Bom and Sá, 2021). Moreover, MPs have been found to bioconcentrate at similar concentrations and similar shapes, polymer types, and sizes at each distinct trophic level in coral reefs (Miller et al., 2023).

Data based on reef-building species (*Acropora muricata*, *Pocillopora verrucosa*, *Porites lutea*, and *Heliopora coerulea*) show that MP concentrations in the carbonate skeleton (up to 84 particles per cm^3) are much higher than those found in other coral tissues (up to 2 particles per cm^3) (Reichert et al., 2021). The MP accumulation process in skeletons is related to growth (Soares et al., 2020; Reichert et al., 2021). Different microplastics (e.g., polyester, polypropylene, and polyethylene) have been detected in annual coral growth bands, mainly between 1964 and 2005, for *Porites* sp. (Krishnakumar et al., 2021). In this context, MP fibers were found inside the coral skeleton, with textile-related rayons and polyester/PET microfibers being the most prevalent (Lim et al., 2022). Moreover, several studies have shown that plastic items facilitate the spawning and early settlement of reef organisms (Crocetta et al., 2020; Carugati et al., 2021; Rizzo et al., 2022), where these MPs may be incorporated into the biological structure and become intrinsic components of their skeletons and tissues.

These findings confirm bioconcentration and reef enrichment, but biomagnification through trophic transfer is not yet evident, as suggested by a study on the Great Barrier Reef (Miller et al., 2023). In this context, the benthic community in coral reefs is an important and overlooked factor as a short-term biological sink that influences the deposition and retention of MPs in reef sediments, which will be discussed in the next section.

5.2. *Reef unconsolidated sediments and rock diagenesis*

High MP concentrations have been found in the unconsolidated sediments of different coral reefs worldwide, such as the Maldives (Patti et al., 2020), South China Sea (Zhang et al., 2019), Indonesia (Cordova et al., 2018), Hong Kong (Cheang et al., 2018), and the Caribbean Sea (Portz et al., 2020) (Fig. 2). Colonies with complex architectures and rough surfaces had the highest number of MPs (size 0.5 mm) in the underlying sediments (Fig. 5). In this regard, the fraction of 0.5 mm particles trapped in the reef sediment (16.58–22.04% for *Stylophora pistillata*) was one to two orders of magnitude higher than the amount trapped in the exposed structure (0.62–2.82%) (Smit et al., 2021). Overall, unconsolidated sediments are likely to be the principal sinks of MPs in coral reefs.

Structural habitats trap particles in reef sediments by reducing bottom shear stress, which hampers sediment resuspension under stormy conditions (Huang et al., 2021). As high-density MPs behave like natural suspended particles, reef organisms composing marine canopies (e.g., corals and sponges) (Critchell et al., 2019; Fernandino et al., 2020; Huang et al., 2021) may also enhance MP enrichment in reef sediments through retention of MPs.

The accumulation of MPs in the reef sediment can be explained by near-bed turbulent kinetic energy, indicating that it is driven by the same hydrodynamic processes that lead to sediment trapping (Smit et al., 2021). MPs in reef sediments showed transport and accumulation patterns similar to those of fine siliciclastic grains (Utami et al., 2021). In addition, a significantly larger fraction of 0.5 mm particles than the larger (2.5 mm) MPs was trapped in the reef sediments (Smit et al., 2021). Deposition processes in reef sediments are related to plastic pollution source areas, hydrodynamic processes (occurring in both low- and high-energy areas), and local processes such as biofouling, interlocking, and the creation of compound grains (Utami et al., 2021).

MPs found in the surface layers of reef sediments are resuspended by bioturbation and processes such as waves, storms, and strong currents (Zhang et al., 2019; Patti et al., 2020). However, the formation of MP deposits in subsurface sediment layers leads to long-time retention processes. The phenomenon of MP enrichment in subtidal reef sediments below the seafloor represents a long-term MP sink (Utami et al., 2021). Benthic complex organisms structures promote MP retention and settlement in the sediment, accounting for more than 90% of the particles trapped in unconsolidated reef sediment (Smit et al., 2021). Furthermore, MPs can accumulate in both high-energy (e.g., reef crests) and low-energy (e.g., lagoons) reef environments (Utami et al., 2021).

Recently, the diagenesis of sedimentary rocks with microplastics have been reported (Fernandino et al., 2020; Santos et al., 2020) (Fig. 7). The process includes the cementation of unconsolidated beach sediments, forming beach rocks, and plastic deposits on sediments and rocks in the foreshore reef region. The diagenesis of beach rocks via carbonate cementation is rapid and enables the union of siliciclastic, bioclastic, and plastic grains in a rock (in addition to other human artifacts, such as metal bottle caps) (Fernandino et al., 2020). Furthermore, Santos et al. (2020) pointed out that molten plastic can provide the main cement in the formation of rock analogs by hardening and/or coating unconsolidated sediments and other substrates, such as beach rocks or even volcanic rocks. Furthermore, erosive micro features, such as dissolution basins, may also enhance the long-term accumulation of plastics, owing to both accumulating unconsolidated sediments and the cementation of this unconsolidated material.

6. Conclusions and what we still need to learn?

This review attempts to determine why reef ecosystems have high concentrations of MPs and, consequently, act as potentially important MP sinks. We describe five characteristics that lead to the reef enrichment by MPs: 1) adhesion on corals at distinct depths; 2) ingestion by reef organisms, trophic transfer, and formation of short-term (i.e., years to decades) sinks for MPs; 3) formation of long-term (i.e., centuries) MP sinks in coral skeletons and subsurface sediments; 4) the complex architecture that reduces bottom shear stress and hampers the sediment resuspension and seafloor turbulent kinetic energy, increasing retention and deposition of MPs; and 5) recent diagenesis in the Anthropocene of sedimentary rocks which form long-term MP sinks.

Together with the long-term deposition in sediments, the accumulation of MPs in the skeleton of corals helps to partially explain the low concentrations of MPs found at the sea surface (the "missing plastic" phenomenon). Based on the data on the four species reported, it has been estimated that corals may remove 0.09–2.82% of bioavailable MPs per year from the waters of shallow tropical reefs (Reichert et al., 2021). Based on these estimates and the fact that the retention of MPs in sediments is one to two orders of magnitude greater (Reichert et al., 2021) than that recorded in reef organisms (Smit et al., 2021), coral reefs may absorb more than 10% of the MPs found in shallow tropical waters annually (combining accumulation in reef organisms and sediments). This is probably an underestimate, considering the existence of other shallow corals (Reichert et al., 2021) and reef organisms, whose potential as sinks requires further analysis. In addition, the deposition of MPs in mesophotic environments (at depths of 30–150 m) and the deep sea, in the case of cold-water corals (Soares et al., 2020), should further increase these estimates. Cold-water reef systems are extensive on the ocean's floor, with high MP concentration rates due to settlement processes. The deep sea is likely to be one of the principal sinks of MPs in the world's oceans (Peng et al., 2018; Woodall et al., 2014) because of the extensive areas of cold-water coral reefs, currents, and the deposition and retention of MPs in deep-sea sediments (Hoegh-Guldberg et al., 2017; La Beur et al., 2019; Soares et al., 2020).

What is clear, however, is that there is still an enormous amount of work to be done to consolidate our understanding of the reef accumulation hypothesis, not only in shallow waters but also in mesophotic and cold-water coral reefs (Soares et al., 2020) that probably trap and harbor even more MPs. In addition, it is necessary to understand how environmental changes, such as those provoked by climate change and increasing pollution, alter the dynamics of MP sinks and sources. In other words, the increase in the mortality rate of animals due to rapid environmental changes may lead to the release of MPs accumulated for years in the tissues, sediments, and skeletons that can return to the environment and contaminate other compartments, such as the water column, making the reef a source rather than a sink of MPs. However, testing this hypothesis requires more extensive research.

Despite the importance of this topic (i.e., plastic pollution) in the United Nations Ocean Decade (2021–2030), further research is needed to understand the role of reefs in MP interception. As the main points to be studied in the future, we highlight three key topics.

1) There is a need to improve the quantification of MPs in different reef compartments (e.g., water, biota, and sediments) and standardize the isolation and extraction of MPs as well as the measurement units. Methods for the sampling and analysis of reef matrices are actively developed (Huang et al., 2020), although a lack of standardization hampers adequate spatial comparison of pollution levels (Supplementary Material 1). For example, some treatments (e.g., samples were ground into powder using a pestle) (Zhou et al., 2023) need to be avoided because they can lead to inaccurate estimation of MP concentration. In this regard, when a sample is milled it can lead to the fragmentation of MPs and thus to an overestimated concentration. Additional examples of methodological flaws include the sampling (e.g., water, sediment, and corals), extraction (e.g., lab contamination), identification of MPs (e.g., absence of chemical analyses of MPs), high proportions of studies that are experiment-based than field-based, low diversity of analyzed coral species. Therefore, the development of unified and standardized protocols for the systematic analysis of distinct matrices (water, sediment, and organisms) is paramount.
2) There is a need to understand which hydrodynamic and biological processes may increase or reduce the retention of MPs in either the sediments or the organisms. The reef "processes" plays a major role in the retention of MPs, either through its biological processes (adhesion, ingestion, trophic transfer) or the sequestration in its sediments. In this context, it is essential to include other types of reef organisms, such as algae, mollusks, polychaetes, sponges, ascidians, and gorgonians, to provide more holistic insights into the processes and levels of MP accumulation. In particular, it is crucial to understand how ingestion rates, benthic species morphology, forest canopy density, and life history strategies influence reef retention and sink processes. We hypothesized that more mature forests with organisms that have a greater surface area and older colonies may have greater potential as sinks than degraded reefs.

The relationship between global degradation of coral reefs and MP pollution should be investigated. Coral reefs are at risk from global environmental changes, such as acidification and warming; marine pollution, including plastics (Hoegh-Guldberg et al., 2017); and activities such as fisheries and mineral extraction (Reed, 2002; Erftemeijer et al., 2012; Magris et al., 2018; Soares et al., 2021). These processes may have a synergistic relationship with MP accumulation; however, this requires further research. In particular, it would be useful to focus on corals because of the unknown risks of destabilization (increased erosion) of the carbonate framework owing to the presence of MPs in the coral skeleton (Hierl et al., 2021) and the impact of the accumulation of MPs on the photosynthesis (Syakti et al., 2019; Mendrik et al., 2021). Decreased carbonate coral growth due to the presence of MPs (Hankins et al., 2021) and the synergetic effects related to the dissolution of the skeleton by acidification of the ocean (Eyre et al., 2018) are potentially key topics. However, this will require further investigation in both the field and laboratory.

3) It is important to determine whether coral reefs also act as sinks for nanoplastics and how this process differs from that of microplastics. For example, Béraud et al. (2022) recorded the presence of nanoplastics in the water (0.09–0.43 particles L^{-1}) and sediments (1.08–71.02 particles g^{-1} DW) of pristine shallow-water reefs, and the concentrations of nanoplastics in the reefs appeared to correlate with those of MPs. Further studies on nanoplastics are necessary to understand the impacts and distributions of nanoplastics in coral reef habitats.

In conclusion, the ocean is key in global environmental changes and related measures to address climate change emergency. Although the importance of reef organisms as carbon immobilizers has been recognized, the exact amount of carbon retained by reef organisms has not yet been determined (Rossi and Rizzo, 2020), and the threats posed by MPs to the efficiency of carbon sequestration from reef organisms are poorly understood or investigated (Shen et al., 2020). Large quantities of MPs in the water column may alter both phytoplankton photosynthesis and growth and zooplankton development and reproduction, leading to trophic crises in marine habitats composed of benthic suspension feeders and threatening ocean carbon sequestration (Rossi and Rizzo, 2020). Furthermore, the synergistic effect of multiple stressors, such as the warming of sea surface temperature (Syakti et al., 2019), ocean acidification, coastal eutrophication, and MP accumulation (Plafcan and Stallings, 2022), also represent a milestone topic that will require a thorough investigation to better understand the potential for the long-term survival of the world's coral reefs.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2023.122509.

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