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Review

Microplastics in the coral reefs and their potential impacts on corals: A mini-review

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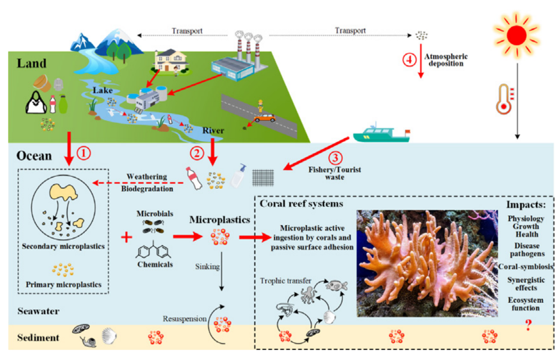
HIGHLIGHTS

- Abundance and distribution of microplastics in coral reefs are firstly reviewed.
- Source and characteristics of microplastics vary from different coral reef regions.
- Microplastic prevalence is attributed to human activities and natural factors.
- Microplastics interact with corals by active ingestion and passive surface adhesion.
- Microplastic exposure influence coral physiology, energetics, growth and health.

GRAPHICAL ABSTRACT



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ABSTRACT

Plastic debris exists worldwide and research on microplastic pollution has gradually spread from the oceans to freshwater and terrestrial systems. Coral reefs not only serve as one of the most charismatic and biodiverse ecosystems on our planet, but also maintain the human harvesting of natural resources and livelihoods of hundreds of millions of people. However, the abundance and distribution characteristics of microplastics in coral reef systems receive little scientific attention. Meanwhile, the impacts of microplastics and nanoplastics on coral health and its potential mechanisms remain further studied. Herein, this review first summarized the current status of microplastics pollution in global coral reefs, especially included (i) abundance and distribution characteristics of microplastics in different media (e.g., seawater, sediment, corals), and (ii) possible sources of microplastics in reef regions. Furthermore, the main interaction mechanisms between microplastics and corals are highlighted. Following this, the direct or indirect impacts of microplastics on coral species are discussed. With the rapid increase of plastic consumption and background of pervasive global coral bleaching, research on marine microplastics must focus on the critical coral reef regions and include a comprehensive knowledge about the distribution, fate, and potential risks from an ecosystem perspective.

Abbreviations: AAS, atomic absorption spectrophotometer; ABS, acrylonitrile butadiene styrene; DDTs, sum of dichloro-diphenyltrichloroethane; EPS, expanded polystyrene; EVA, ethylene vinyl acetate; FTIR, Fourier-transform infrared spectroscopy; HDPE, high-density polyethylene; ICP-MS, inductive couple plasma mass spectrometry; LDPE, low-density polyethylene; Mt, million tonnes; PAEs, phthalate esters; PA, polyamide; PAHs, polycyclic aromatic hydrocarbons; PAN, polyacrylonitrile; PC, polycarbonate; PCBs, polychlorinated biphenyls; PE, polyethylene; PEST, polyester; PET, polyethylene terephthalate; PEU, polyether urethane; PP, polypropylene; PP-PE, polypropylene-polyethylene copolymer; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses; PS, polystyrene; PU, polyurethane; PVA, polyvinyl acetate; PVC, polyvinyl chloride; SEM-EDAX, scanning electron microscope fitted with energy dispersive X-ray spectroscopy; UA, urethane alkyd.

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Contents

1. Introduction

In the "Plastic Era", multifarious plastic products have been widely used in various aspects of our life and brought great convenience to humans. With the growing demands, the annual global plastic products reached about 359 million tonnes (Mt) in 2018 from 348 Mt. in 2017 (PlasticsEurope, 2019). Because of the overuse, mismanagement and durability of plastics, almost 6300 Mt. plastic wastes had been continuously generated from 1950 to 2015, 79% of which entered landfills or natural environments (Geyer et al., 2017). It was estimated that the amount of plastic wastes discharged into the ocean annually has reached Mt. level (Jambeck et al., 2015; Lebreton et al., 2017). Large plastic wastes in different environments can be gradually broken into the microscopic plastic fragments through the long-lasting weathered and degradation behavior, such as mechanical abrasion, hydrolysis, UV photodegradation, biodegradation, and even biological ingestion (Dawson et al., 2018; Hernandez et al., 2019; Liu et al., 2020). The plastic fragments <5 mm in diameter were recognized as microplastics (Arthur et al., 2009; Thompson et al., 2004), while nanoplastics were generally termed as plastic particles <100 nm or 1 μm due to lack of a standardized specified size boundaries (Hartmann et al., 2019; Koelmans et al., 2015). In addition, the environmental sources of nano- and micro-plastics are derived from either primary (from microbeads in consumer products or industrial abrasives and accidental pellet spills) or secondary (fragmentation/degradation from large plastics) (Alimi et al., 2018; Hernandez et al., 2019; Liu et al., 2020; Rochman et al., 2015).

Research on the occurrence, distribution and impacts of microplastics began in 2004 with a pioneering work put forward by ecologist Richard Thompson, and it has been a hot spotlight in marine ecology for over a decade (Kane et al., 2020; Law and Thompson, 2014; Thompson et al., 2004; Zhang et al., 2020a). Recently, scientists have expanded their focus from the oceans to freshwater (Alimi et al., 2018; Eerkes-Medrano et al., 2015; González-Pleiter et al., 2020; Li et al., 2018), terrestrial environments (Brahney et al., 2020; de Souza Machado et al., 2018; Rillig and Lehmann, 2020; Rochman, 2018), and even atmosphere (Allen et al., 2019; Brahney et al., 2020; Liu et al., 2019a; Zhang et al., 2020b). The issues about "microplastic cycle" and their complex interactions with biogeochemistry (e.g., nitrogen, carbon), bioavailability, trophic transfer, human health, and even climate change have gained significant interest from researchers (Bank and Hansson, 2019; Carbery et al., 2018; Rochman et al., 2019; Rochman and Hoellein, 2020; Shen et al., 2020). In nature, weathered behaviors can impact how plastic items ultimately fragmented into microplastics or nanoplastics, and the extent to which they leach toxic additives into the environment (Chen et al., 2019; Liu et al., 2019b). Moreover, due to their ubiquity, hydrophobicity, microscopic and durability, microplastics can serve as carriers for various associated chemical contaminants (e.g., organic pollutants, heavy metals) (Brennecke et al., 2016; Godoy et al., 2019; Teuten et al., 2007; Wang et al., 2018), and colonized microbial communities named "Plastisphere" (Amaral-Zettler et al., 2020; Wang et al., 2021; Zettler et al., 2013). Microplastics, as diversified and complex contaminants, have raised the wide concern about their potential toxic effects on diverse organisms and ecosystems due to their persistence, ubiquity, and diversity of plastic polymer, type, size, morphology, color, leaching additives, adsorbed environmental chemicals, and surface biofilm (Rochman et al., 2019).

Even though covering only less than one-tenth of 1% of the ocean surface, coral reef ecosystems are crucial to marine biodiversity maintenance, global climate mitigation, human harvesting of natural resources and livelihoods of more than 275 million people (Burke et al., 2011; Spalding and Brown, 2015). Yet, they are highly vulnerable and suffer from anthropogenic damages, and environmental stressors such as rapid climate change, ocean acidification, marine pollution and pathogen-induced disease (Hoegh-Guldberg et al., 2007; Hughes et al., 2018). Plastic pollution can be considered as an emerging threat to the coral reefs due to their complex interactions (e.g., entanglement/catches, covering/smothering) (de Carvalho-Souza et al., 2018; Yoshikawa and Asoh, 2004). In a field investigation in 124,000 reef-building corals from 159 coral reefs across the Asia-Pacific oceans, Lamb et al. (2018) found the estimated 11.1 billion large plastic items were "trapped" in coral reefs, with a predicted increase of 40% by 2025. These benthic macroplastics (diameter > 50 mm) increased the susceptibility of reef-building coral disease from 4% to 89% and more easily affected the structurally complex corals, but their pathogenic mechanisms need to be further studied. Plastic items can result in the physical abrasions and injuries to the coral tissues and promote the invasion of pathogens and ciliated protozoan, causing the coral disease such as skeletal eroding band (Lamb et al., 2016; Page and Willis, 2008). Also, plastic items can bring about foreign microbial communities (e.g., coral opportunistic pathogens) and might disturb the normal host-symbiont relationships. For instance, the floating plastic debris can be served as a vector for the *Rhodobacterales* and *Halofolliculina* spp. that are considered as the opportunistic pathogens associated with outbreaks of coral diseases (e.g., white syndromes, skeletal eroding band) (Dang et al., 2008; Goldstein et al., 2014). Similarly, microplastics in coral reef regions can be enriched with the disease-caused microbial communities such as *Vibrionaceae*, *Rhodobacteraceae* and *Flavobacteraceae*, which are the pathogens of coral tissue damage and bleaching (Feng et al., 2020). In addition, two studies contrasted the difference in effects of 500 μm HDPE microplastics and 10 × 10 cm LDPE film on cold-water corals (Chapron et al., 2018; Mouchi et al., 2019). Macroplastics, as a "physical barrier" for food supply and energy acquisition, increase the coral polyp activities and polyp "cap" structure overgrows to gain food, but it significantly reduced zooplankton capture rates and skeleton growth rates. In contrast, the long-term exposure of microplastics caused the species-specific effects (e.g., impaired prey capture and growth rates, decreased skeletal growth rates, reduced coral calcification) on corals. Thus, the impacts of microplastics need to be paid more attention because the ubiquitous microplastics may directly or indirectly affect coral health by a multitude of pathways.

Although two marine issues (coral reef degradation and microplastic pollution) have raised appreciable attention, knowledge about the occurrence, fate, and impact of microplastics in coral reef systems remain still limited. In the last few years, researchers have gradually begun to investigate the abundance and distribution characteristics of microplastics in coral reef regions (Ding et al., 2019; Imhof et al., 2017; Cordova et al., 2018; Reisser et al., 2013). The investigated environmental media in coral reefs included seawater (Jensen et al., 2019; Nie et al., 2019), sediments (Patterson et al., 2020; Vidyasakar et al., 2018), and coral samples (Ding et al., 2019; Rotjan et al., 2019). Furthermore, the potential impacts of microplastics on coral species in laboratory conditions have been studied in recent five years. Since 2015, Hall et al. (2015) first put forward to a work about the PP microplastic ingestion by the mound-shaped stony scleractinian coral *Dipsastrea pallida* with a feeding rates of ~50 μg cm^{-2} h^{-1}, and found that ingested microplastics retained in the mesenterial tissue of coral gut cavity. Subsequently, some laboratory studies revealed that microplastic active ingestion and passive surface adhesion can affect coral energetics, growth and health, with adverse consequences for feeding behavior, photosynthetic performance, energy expenditure, skeletal calcification, and even tissue bleaching and necrosis (Lanctôt et al., 2020; Reichert et al., 2018; Savinelli et al., 2020; Syakti et al., 2019; Tang et al., 2018). Additionally, other potential threats (e.g., combined effects of microplastics and associated chemicals, disease-causing pathogens induced by microplastics, impacts on coral-zooxanthellae symbiosis, coupled impacts with climate change) to coral species are gradually receiving attention (Aminot et al., 2020; Feng et al., 2020; Okubo et al., 2018; Okubo et al., 2020; Su et al., 2020). A comprehensive understanding of the occurrence, sources, and hazards of microplastics in the coral reef systems is urgently needed.

Over the past decade, the occurrence, distribution characteristics, and ecotoxicological effects of microplastics have been widely reviewed in aquatic environments such as freshwater and marine (Hidalgo-Ruz et al., 2012; Li et al., 2018; Rochman and Hoellein, 2020). Nevertheless, no attempts have been performed to comprehensively summarize the occurrence and fate of microplastics in coral reef systems. The present review aims to summarize the known information including: (i) abundance, distribution characteristics and fate of microplastics in global coral reef regions; (ii) interaction mechanisms between microplastics and corals; and (iii) potential impacts of microplastics on coral species. This work is expected to provide a meaningful perspective for better understanding the fate and impacts of microplastics in coral reef systems.

2. Methods of literature review

According to the approach of PRISMA (Moher et al., 2009), we conducted a literature review using databases (ISI Web of Science and Science Direct) and published volumes in some environmental field journals (e.g., Environmental Science & Technology, Science of the Total Environment, Environmental Pollution, Marine Pollution Bulletin), for studies published up to September 2020. The keyword terms used in our searches were included: microplastics, plastic debris, coral and coral reef. Furthermore, we consulted the article contents and reference lists in the searched literatures, and then tracked back to other relevant topic literatures. After a selection process, we identified 43 research articles. From them, this review presents the main information on (i) microplastic pollution status in the coral reef systems and (ii) direct and indirect effects of microplastics on coral species.

3. Abundance and distribution of microplastics in coral reef systems

Based on an assessment report published by World Resources Institute in 2011 (https://www.wri.org/publication/reefs-risk-revisited), the global coral reef areas were estimated to cover 249,713 km^2 of ocean surface and roughly divided into six reef regions, including the Southeast Asia (28% of global reef areas), Pacific (26%), Australia (17%), Indian Ocean (13%), Atlantic (10%), Middle East (6%) (Burke et al., 2011). To date, microplastics are ubiquitous in the marine environments, yet only limited coral reef regions have been investigated, as shown in Fig. 1. According to these available investigations in recent years, the abundance and distribution characteristics of microplastics in the coral reef systems (including seawater, sediments, and corals) were summarized in Table 1. Researchers have documented that microplastic abundance in the surface water of coral reefs generally ranges from zero to tens of thousands of items/m^3, while these in sediments and corals are difficult to quantify due to lack of a relatively standardized unit or enough available data. Also, microplastics in coral reefs are mainly composed of fibers, pellets, fragments, films, and granules, with the board

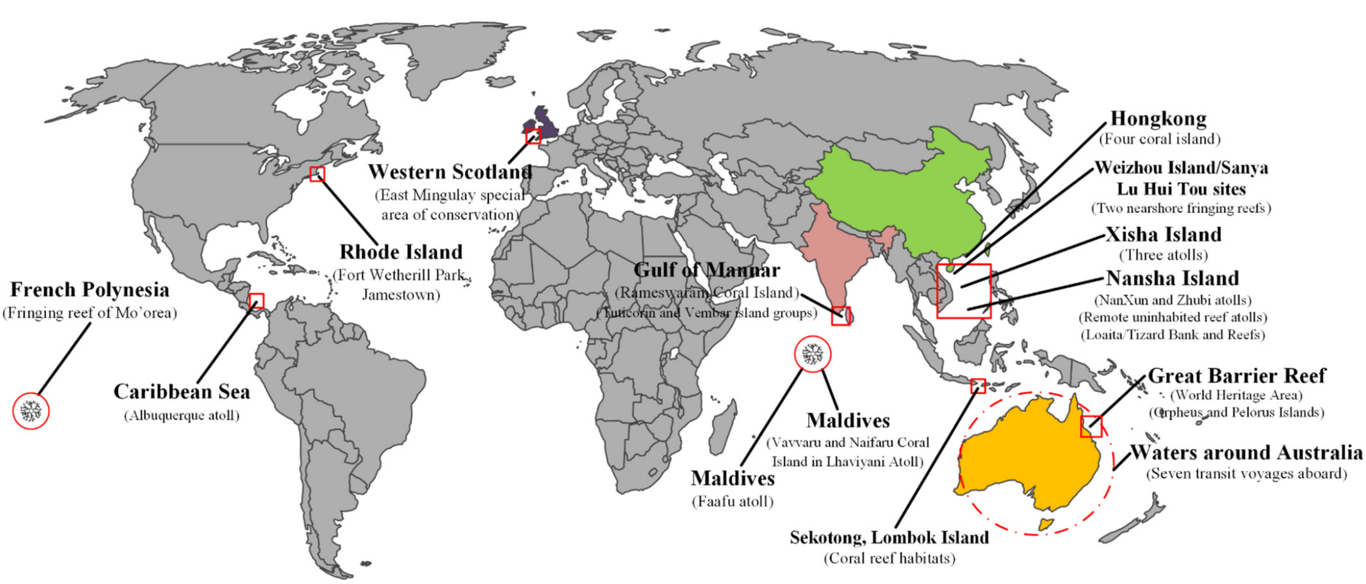

Fig. 1. Worldwide coral reef sampling regions of microplastic investigations.

Table 1
Microplastic abundance and distribution in the coral reef systems.

Investigation regions	Media	Analytical methods	Size	Abundance	Polymer type	Shape	Color	Source	Ref.
Inhabited Naifaru coral island in Lhaviyani Atoll, Maldives (Indian Ocean)	Sand/sediment in fore reef (8 sites); in reef flat (8 sites); in beach (6 sites)	In-situ sampling; Extraction; Microscope inspection	63 μm-4 mm (mostly <0.4 mm)	277.90 ± 24.98 items/kg (55–1127.5 items/kg) (249.81 ± 23.23, 333 ± 31.2, 241.88 ± 15.37 items/kg, respectively)	–	Fragment and filament	Mostly blue, followed in order by red, grey, orange, and black	Long-distance transport from neighboring islands or coastal countries; local plastic waste mismanagement	(Patti et al., 2020)
Albuquerque atoll in the Caribbean Sea (Atlantic)	Sand/sediment; Seawater	(In-situ sampling; Trawl sampling); Extraction; Microscope inspection	1-5 mm; >80 μm	90 items/m^2; 0.059 items/m^3	–	Mostly fragment	Orange/brown> white> green> grey> blue	Fishing activities and sea-based sources	(Portz et al., 2020)
Tuticorin and Vembar island groups in Gulf of Mannar, India (Indian Ocean)	Seawater (five sites)	Trawl sampling; Extraction; Microscope inspection; FTIR spectroscopy	0.8–5 mm (mostly <3 mm)	60,000–126,600 items/m^3	PE, PP, PS, PA, PET, PVC, PEST, PEU, PVA and alkyd resin (mostly PE and PP)	Fiber>film, foam> fragment	Mostly transparent, blue, black and red	External plastic sources due to local water movement	(Patterson et al., 2020)
	Sediment (five sites)	Van-Veen grab In-situ sampling; Extraction; FTIR spectroscopy	0.8–5 mm (mostly 1–5 mm)	50–103.8 items/kg	PE, PP, PS, PA, PEST, PET, PVC, PVA and PEU (mostly PE and PP)	Fragment> fiber>film> foam	Mostly transparent, blue, black and red		
Seventeen remote uninhabited reef atolls in Nansha Islands, South China Sea (Southeast Asia)	Seawater (24 samples)	Trawl sampling; Extraction; Microscope inspection; FTIR spectroscopy	20 μm-5 mm (Mostly <3 mm)	0.0556 ± 0.0355 items/m^3 (0.0112–0.149 items/m^3)	PP > PE > PP-PE > PAN>UA > others	Fragment> fibers>film	Transparent> green>blue> yellow> black>red> white	Nearby residential islands; fishery activities	(Tan et al., 2020)
Nanxun Reef in Nansha Islands, South China Sea (Southeast Asia)	Seawater (15 samples)	Water sampler sampling; Microscope inspection; Raman spectroscopy	48 μm-5 mm (Mostly <0.5 mm)	1733 items/m^3 (1250–3200 items/m^3)	PVC > PA = PE > PP	Pellet, followed by fragment, fiber and film	Blue> white> transparent> others	Fishery activities; human domestic sewage	(Nie et al., 2019)
Zhubi Reef in Nansha Islands, South China Sea (Southeast Asia)	Seawater (30 samples)	Water sampler sampling; Microscope inspection; Raman spectroscopy	50 μm-5 mm (Mostly <0.5 mm)	4933 ± 1369 items/m^3 (1400–8100 items/m^3)	PP > PA > PS > PVC > others	Fiber and pellet, followed by fragment and film	Blue> transparent> pink>others> green	Fishery activities; emissions from coastal cities	(Huang et al., 2019)
World Heritage Area in central Great Barrier Reef (Australia)	Seawater (22 samples)	Trawl sampling; Microscope inspection; FTIR spectroscopy	0.355–5 mm (mostly 0.33–3 mm)	547 items in 22 tows (0.04–0.48 items/m^3)	Synthetic ($n = 36\%$), semi-synthetic ($n = 39\%$), naturally-derived ($n = 25\%$)	Fiber ($n = 75\%$), particle ($n = 25\%$)	Mostly black, blue, white, and red	Land-based sewage effluent discharges	(Jensen et al., 2019)
Two atolls (Xisha Islands, Nansha Islands) and two nearshore fringing reefs (Weizhou Island, Sanya Lu Hui Tou sites), South China Sea (Southeast Asia)	Sand/sediment (14 sites)	In-situ sampling; microplastic extraction; Raman spectroscopy	0.3–5 mm (mostly 300μm-1 mm)	60 ± 3–610 ± 11 items/kg, 40 ± 4–100 ± 2 items/kg, 60 ± 2–90 ± 5 items/kg, and 50 ± 3–530 ± 7 items/kg, respectively	PP > PE, PET, PC, nylon	–	Red, transparent, white, blue, green	–	(Zhang et al., 2019)
Three atolls in Xisha Islands, South China Sea (Southeast Asia)	Seawater (20 samples)	Water sampler sampling; Microscope inspection; FTIR spectroscopy	7–4856 μm (mostly 20–330 μm)	Outer reef slopes, reef flats, and lagoons (200–11,200, 1000–12,200, and 1000–45,200 items/m^3, respectively)	Rayon fiber> PET	Fiber> fragment> granule> film	Red> black> blue> others	–	(Ding et al., 2019)
	Coral (27 samples)	In-situ sampling by diving and snorkeling; microplastic extraction from coral skeleton	24–4729 μm (mostly 500–5000, 24–330 μm)	1.0–44.0 items/individual (0.02–1.3 items/g)	Rayon fiber> PET	Fiber> fragment> granule	Black> blue> red> others		

		surface and inside; Microscope inspection; FTIR spectroscopy							
Fort Wetherill Park (Jamestown) in Rhode Island, United states (Atlantic)	Coral (4 colonies samples)	In-situ sampling; microplastic extraction from coral polyp; FTIR spectroscopy	40–5000 μm	112 items/per polyp	PA > polyester> synthetic cellulose fibers>PVC >fiber reinforced plastic with epoxy resins	Fiber> round particles> irregularly-shaped particles	–	–	(Rotjan et al., 2019)
Near Loaita /Tizard Bank and Reefs (seven reefs) in the Nansha Islands, South China Sea (Southeast Asia)	Seawater (12 sites)	Trawl sampling; microplastic extraction; Microscope inspection; FTIR spectroscopy	1.6–5000 μm (mostly 50,500 μm)	0.469 ± 0.219 items/m^3 (0.148–0.842 items/m^3) (Loaita reefs: 0.57 ± 0.14 items/m^3, Tizard Reefs: 0.33 ± 0.24 items/m^3)	Mostly PET fiber	Granule (urethane alkyd), fiber, fragment, pellets and film (Mostly Granule, fiber, fragment)	Blue, transparent, black, green, tawny, orange, red, yellow, grey, white, pink	Activities of local military personnel stationed on islands and fishery nearby waters	(Wang et al., 2019)
East Mingulay special area of conservation, Western Scotland (Atlantic)	Microplastics in benthic faunal samples (112 organisms)	In-situ sampling; microplastic extraction; Raman spectroscopy	–	–	–	Fiber and particle	–	Fishery activities and debris originating from coastal communities	(La Beur et al., 2019)
Rameswaram Coral Island, Gulf of Mannar (Indian Ocean)	Sediment (20 sites)	In-situ sampling; extraction; FTIR spectroscopy	1.01–4.75 mm (60.8%); 4.75–200 mm (30%); >200 mm (9.2%)	245 micro- plastics; 123 meso-plastics; 37 macro- plastics	PP > PE > PS > nylon> PVC	Irregular shape> fiber>pellet	White> green >blue > yellow> black>others	Tourist activities and Fishery activities	(Vidyasakar et al., 2018)
Faafu atoll, Maldives (Indian Ocean)	Seawater with neuston (11 samples)	Trawl sampling; Microscope inspection; FTIR spectroscopy	330 μm-5 mm	0.12 ± 0.09 items/m^3 (0.03–0.65 items/m^3)	PE, PP, PA, PS, PU	–	–	Inner reef/land based sources	(Saliu et al., 2019)
Faafu atoll, Maldives (Indian Ocean)	Seawater (6 samples)	Trawl sampling; Microscope inspection; FTIR spectroscopy	200–5000 μm	0.26 items/m^3 (0.02–0.48 items/m^3)	PE, PP, PS, PVC, PET, PU	–	–	Burning plastic waste	(Saliu et al., 2018)
	Beach sediment (6 samples)	In-situ sampling; Microplastic extraction; Microscope inspection; FTIR spectroscopy	1-5 mm visible plastic particles; 50 μm-1 mm not-visible particles	1–5 mm 22.7 ± 10.5 items/m^2 (4.2–38.5 items/m^2); <1 mm microplastics (197–822 items/kg)	Visible particle: PE, PP, PEST; Not-visible particle: PE, PP, PA, PS, cellophane and PVC	Visible: fragment> foam> filament> film> pellet; Not-visible: fragment> filament	–		
Sekotong, Lombok Island, Indonesia (Southeast Asia)	Sediment (10 sites)	In-situ sampling with shovel; Microplastic extraction; Microscope inspection; FTIR spectroscopy	0.45–5000 μm (mostly <1000 μm)	48.3 ± 13.98 items/kg (35–77 items/kg)	PS, PE, PP (mostly PS)	Foam> fragment> granule > fiber	–	Usage of styrofoam, food and beverage packages; fishery activities	(Muhammad R. Cordova, 2018)
Four coral island (Double Island, Port Island, Sharp Island and Bluff Island), Hong Kong urban area (Southeast Asia)	Sediment (24 samples, 4 island sites)	In-situ sampling; Microplastic extraction; Microscope inspection; FTIR spectroscopy	0.3–5 mm	194.5 ± 49.9 items/kg (171.7 ± 57.6–223 ± 51.4 items/kg)	PE > PET> PP > PS > PVC > others	Fiber>film> fragment> styrofoam	–	Human activities (fishery, sightseeing); sewage discharge and illegal dumping	(Cheang et al., 2018)
Fringing reef of Mo'orea, French Polynesia (Pacific)	Seawater	Trawl sampling; Microscope inspection	0.05–5 mm	0.74 items/m^2 sea surface area	–	–	–	–	(Connors, 2017)
Remote Vavvaru Island in Lhaviyani Atoll, Maldives (Indian Ocean)	Sand sediment in accumulation zones and intertidal line (6	In-situ sampling with shovel; Microscope inspection; FTIR spectroscopy	1–5 mm; 5–25 mm; >25 mm	1029 ± 1134 items/m^2 in accumulation zones; 35.8 ± 42.5 items/m^2	Accumulation zones: PE > PS > PP > ABS >others; Intertidal line: PE > PP > PS > other	Accumulation zones: styrofoam> foil> fragment> pellet> fiber; Intertidal line:	–	Population density; intensive human activities	(Imhof et al., 2017)

(continued on next page)

Table 1 (*continued*)

Investigation regions	Media	Analytical methods	Size	Abundance	Polymer type	Shape	Color	Source	Ref.
	and 42 samples, respectively)			in intertidal line		fragment> pellet>tar> styrofoam> foil>fiber			
Great Barrier Reef waters adjacent to Orpheus and Pelorus Islands(Australia)	Seawater (3 sites)	Trawl sampling; FTIR spectroscopy	100–500 μm	2 items/11 m^3	PU, PS and PEST	Fiber, fragment	–	Breakdown of larger packaging and fishing items)	(Hall et al., 2015)
Waters around Australia (Australia)	Seawater (57 sites, seven transit voyages aboard Australian vessels)	Trawl sampling; Microscope inspection; FTIR spectroscopy	839 plastic pieces (0.4–82.6 mm, mostly microplastics with a mean size of 4.9 mm)	4256.46 ± 757.79 items/km^2 (0–48,895.6 items/km^2); 8966.3 ± 1330.75 items/km^2 in vertical wind-mixing	PE, PP, EPS, EVA (mostly PE and PP)	Hard plastic, soft plastic, plastic line, Styrofoam, pellet (mostly hard and soft plastic)	White /transparent >blue>others	Fragmentation of larger plastic objects (e.g. packaging and fishing items)	(Reisser et al., 2013)

Note: 1. Based on the *Reefs at Risk Revisited 2011* of WRI (World Resources Institute), the worldwide coral reefs were divided into six regions including Southeast Asia, Pacific, Australia, Indian Ocean, Atlantic, Middle East; 2. Herein, the minimum filtered mesh size is considered as the detected threshold value of wild-collected microplastics.

detected sizes and diverse colors. The common plastic polymers mainly include PP, PET, PA, PVC, PE, PS, PU, PP-PE, PAN and UA, which predominantly originated from waste emissions from coastal cities and the intensive fisheries.

Microplastics in seawater, sediments and coral samples have been investigated. The analytical methods of microplastics in coral reefs were mainly consisted of sampling (e.g., trawl, water sampler, in-situ sediment sampling), extraction (e.g., removal of organic matter, flotation, filtration), microscope inspection, and polymer identification (e.g., Raman, FTIR spectroscopy). Noteworthy, the coral reef regions in the Southeast Asia is a hotspot of microplastic field investigation. For example, Cordova et al. (2018) investigated the coral sediments of ten sites in Sekotong, Lombok Island of Indonesia, and found that the average concentration of microplastics is 48.3 ± 13.98 items/kg. In their results, PS was the most abundant microplastic types and plastic shapes were mainly consisted of foam, fragment, and granule. Another study conducted in coral seabed sediments of four coral islands in Hong Kong by Cheang et al. (2018) showed that the concentrations of microplastics (0.3–5 mm) ranged from 171.7 ± 57.6 to 223 ± 51.4 items/kg and their dominating polymer types were PE and PET, followed by PP, PS, PVC. In addition, Zhang et al. (2019) investigated the microplastic abundances of sands/sediments from four coral reef islands in the South China Sea. Their results demonstrated that the concentrations of microplastics (0.3–5 mm) in two atolls from Xisha and Nansha Islands, and two nearshore fringing reefs from Weizhou Island and Sanya Lu Hui Tou sites) were 60 ± 3 to 610 ± 11 items/kg, 40 ± 4 to 100 ± 2 items/kg, 60 ± 2 to 90 ± 5 items/kg, and 50 ± 3 to 530 ± 7 items/kg, respectively. Interestingly, Ding et al. (2019) investigated the abundance of microplastics in seawater, coral and fish samples in three atolls of Xisha Islands in the South China Sea. As shown in their survey, the abundances of microplastics (7–4856 μm) in the outer reef slopes, reef flats, and lagoons were 200–11,200, 1000–12,200, and 1000–45,200 items/m^3, respectively. Then, they extracted microplastics in the surface and inside of coral skeleton by a two-step process including density flotation and skeleton-dissolved treatment, and identified microplastics (24–4729 μm) in corals with a concentration of 1.0–44.0 items/individual (0.02–1.3 items/g). Also, the microplastic distribution characteristics (e.g., size, polymer type, shape, color) in seawater were more similar to these in fish gills than that in fish gastrointestinal tracts or coral samples. Additionally, the distribution characteristics of microplastics in the reefs of Nansha Islands from South China Sea have been continuously investigated. First, microplastic abundance of surface seawater at Zhubi Reef ranged from 1400 to 8100 items/m^3 and more than 80% of them were < 0.5 mm in size (Huang et al., 2019). Then, another study by Nie et al. (2019) recorded the concentrations of microplastics (48 μm-5 mm) with 1250–3200 items/m^3 in surface water at the Nanxun Reef, and observed that blue microbeads accounted for the majority of microplastic types, while the collected fish species would like to ingest blue and transparent fibers that resembled with their natural prey. Somewhat differently, the microplastic abundance of seawater in Near Loaita/Tizard Bank and Reefs (seven reefs) in the Nansha Islands was lower, with a concentration ranging from 0.148–0.842 items/m^3 (Wang et al., 2019). They also observed a variety of polymer types, shapes, and colors of microplastics, reflecting the complexity of types and sources in waters from Nansha Islands. Recently, the microplastic pollution in remote uninhabited reef atolls from Nansha Islands was examined through the trawl sampling (Tan et al., 2020). In their results, the abundance of microplastics (20 μm-5 mm) in surface water was only 0.0112–0.149 items/m^3 and more than 70% of microplastics was <3 mm in size. By comparison of three investigations in Nansha Islands, evidences demonstrated that the intensity of human activities (e.g., human waste emissions, fishery activity) may be the dominant factor affecting the microplastic pollution in reef regions. In the Pacific reef regions, Connors (2017) found microplastics (0.05–5 mm) in the seawater of fringing reef of Mo'orea at French Polynesia, with a concentration of

0.74 items/m^2 sea surface area. Also, diverse microplastics (0.031–2.44 mm) were detected in 21% of the guts of four fish species captured from Mo'orea Island waters, suggesting the presence of microplastics in this coral reefs (Garnier et al., 2019).

In the Great Barrier Reef from Australia reef regions, microplastics have become contaminants of emerging concern (Kroon et al., 2020; Kroon et al., 2018). For the first time, the presence of plastic pieces (0.4–82.6 mm, mostly microplastics <5 mm) were detected in 57 sampling sites from the Waters around Australia with an average concentration of 4256.46 $\pm$ 757.79 items/km^2 (Reisser et al., 2013). Also, Jensen et al. (2019) conducted a surface tows at near eleven inshore and eleven offshore reefs, and collected 547 complex micro-debris (0.355–5 mm, 0.04–0.48 items/m^3, mostly microfibers) was consisted of the synthetic ($n = 36\%$), semi-synthetic ($n = 39\%$) and naturally-derived items ($n = 25\%$). Based on their study, the ingestion of micro-debris characteristics (e.g., polymer types, shape, colors) by Lemon damselfish (a coral reef fish) collected in this region had no significant relationship with the microfiber in the surface water, thus indicating the complexities in sources and fates of microplastics from coral reefs. Additionally, Hall et al. (2015) reported up to two microplastics (size 100–500 μm) per 11 m^3 seawater from the Great Barrier Reef waters adjacent to Orpheus and Pelorus Islands. In the Indian Ocean reef regions, the presence of macro-, meso- and microplastics in the sand sediment of accumulation zones and intertidal line from the remote Vavvaru Coral Island in Lhaviyani Atoll (Maldives) was first reported (Imhof et al., 2017). Following this, Patti et al. (2020) investigated microplastic abundance in sediments around the Naifaru coral island in Lhaviyani Atoll, Maldives, and found that the average concentration of microplastics is 277.90 $\pm$ 24.98 items/kg. Notably, the "inner atoll" region and "reef flat" environment contained the highest abundance of microplastics, while concentration and size across these regions have no significant relationship. In addition, Saliu et al. (2018) analyzed the seawater and sediments samples in the Faafu Atoll of Maldives. Results demonstrated that the mean microplastic abundance was 0.32 $\pm$ 0.15 items/m^3 in seawater and 22.8 $\pm$ 10.5 items/m^2 in beach sediments, whose primary plastic polymers included PE, PP, PS, PVC, PET, and PA. Subsequently, they found the ng/g levels of plastic-derived PAEs in the plankton and scleractinian corals in the Faafu Atoll (Saliu et al., 2019). Another study done by Vidyasakar et al. (2018) found the abundance of white colored and irregular shaped plastic debris in the sediment samples of Rameswaram Coral Island from Gulf of Mannar, India. Currently, Patterson et al. (2020) surveyed the distribution characterastics of microplastics and heavy metals in the Tuticorin and Vembar island groups from Gulf of Mannar, India. Notably, microplastics ranged from 60,000–126,600 items/m^3 with the most abundant fibers (1–3 mm) in seawater and from 50 to 103.8 items/kg with the most abundant fragments (3–5 mm) in sediments, and PE and PP were the most common plastic polymer. In the Atlantic reef regions, microplastics were observed in benthic faunal samples (112 organisms) in the East Mingulay special area of conservation, Western Scotland (La Beur et al., 2019). An interesting investigation by Rotjan et al. (2019) into the microplastics in four wild-captured coral colonies from Rhode Island found that the microplastic abundance was 112 items/per polyp with the most abundant fibers and the polymer mainly comprised PA, PEST, and synthetic cellulose-based fibers. Recently, Portz et al. (2020) reported that the average microplastics (1–5 mm) on beach sediment are 90 items/m^2 and plastic debris (>80 μm) in the atoll inner lagoon are 0.059 items/m^3 in the Albuquerque atoll, Caribbean Sea, with the diverse colors and complex plastic sources. In brief, the abundance and distribution characteristics (e.g., concentration, polymer types, size, shape, color) of microplastics in surface seawater and sediment samples varied from different coral reef regions. Thus, the effects of different factors (e.g., sampling area, analytical methods, water movement, coral species) on the reported microplastic abundance in reef regions need further assessment in future studies. Furthermore, the sources of microplastics are complex and affected by human activities and natural factors. Also, the microplastic pollution status in Middle East reef regions remains so far uninvestigated.

As there are no standardized analytical methods for microplastics, it is difficult to contrast microplastic abundances in different environmental media, especially reef sand/sediments. Besides, although the samples of surface seawater and sediments in reefs have been monitored, the distribution characteristics of microplastics in reef skeleton surface and inside are still poorly understood. In reality, the microplastic adhesion to the coral reef skeletal surface might be significantly higher than the suspension in environmentally realistic seawater or microplastic ingestion by corals (Corona et al., 2020; Martin et al., 2019). Ding et al. (2019) developed a two-step combined method including density flotation with the saturated sodium chloride solution and skeleton dissolution with HCl solution, and extracted microplastics from the surface and inside of field coral skeleton. Thus, a standardized, operable and environmentally-friendly analytical method should be developed to evaluate the microplastic pollution status in worldwide coral reef regions. Furthermore, the sources, distribution patterns, and composition of microplastics vary from various reefs, because complex environmental factors, such as plastic fragmentation and transport mechanisms, sampling areas, and water movement, are highly variable.

Additionally, the knowledge gaps for nanoplastics in coral reefs are even larger yet due to limitations of classical sampling and analytical techniques. Although multiple techniques have been applied to the separation (e.g., flotation, filtration), identification (e.g., FTIR, Raman spectroscopy) and quantification of microplastics in different environmental matrices, most of them are not suitable for detection of nanoplastics because of the size discrepancy. Therefore, more efforts need to develop advanced analytical techniques to improve the resolution and sensitivity of nanoplastics determination (Li et al., 2020). For example, developing suitable membrane materials (e.g., ultrafiltration membrane) or efficient separation process (e.g., field flow fractionation, cloud point extraction, pressurized fluid extraction, thermal hydrolysis) is meaningful. Further developments of the spectroscopic techniques (e.g., nano-FTIR absorption spectroscopy, nano-Raman Tweezers), advanced mass-spectrometry (MS)-based methods and other thermal analysis method are helpful for the nondestructive identification of nanoplastics. Considering its greater toxicity caused by the nanoscale size, surface chemical properties and in-vivo accessibility (Shen et al., 2019), the field investigation and risk assessment of nanoplastics in coral reef regions is also urgently required.

4. Potential impacts of microplastics on corals

According to the existing studies, the potential mechanisms between microplastics and corals include microplastic ingestion and exposure, combined effects of microplastics and associated chemical contaminants, coral disease induced by plastics, and impacts on coral-zooxanthellae symbiosis. The knowledge regarding the different effects of microplastics on coral species was summarized in Table 2.

4.1. Effects of microplastic ingestion and exposure

Research on the effects of microplastic ingestion by corals started in 2015 with a pioneering work put forward by Hall et al. (2015). Their results showed that blue PP microplastics (10–2000 μm) can be ingested by scleractinian corals *Dipsastrea pallida* with a feeding rates of 1.2–55 μg plastic cm^{-2} h^{-1}, and retained in the mesenterial tissue of coral gut cavity for more than 24 h. According to the subsequent studies, the majority of ingested microplastics may be expelled via the cleaning mechanisms (e.g., direct interaction, mucus production) after 1–2 days, but the potential impacts of retained microplastics on corals are non-negligible (Allen et al., 2017; Hankins et al., 2018; Rotjan et al., 2019).

The underlying mechanism about microplastic ingestion by corals is still an open topic. Existed knowledge shows that the weathering process of microplastics and presence of natural food can influence

Table 2
Recent studies on the potential impacts of microplastics on corals.

Coral species	Microplastics exposure				Results	Ref.
	Polymer	Size	Conc.	Duration		
Scleractinian coral (*Stylophora pistillata*)	PE	106–125 μm	5000, 50,000 items/L	4 weeks	Photosynthetic performance in the coral symbiont is affected at 50000 items/L concentration; cause subtle but significant alterations to metabolite profiles of coral; microplastics disrupt host-symbiont signaling and that corals respond to this interference by increasing signaling and chemical support to the symbiotic zooxanthellae algae	(Lanctôt et al., 2020)
Hexacorallia (*Zoanthus sociatus*)	LDPE, PVC	63–125 μm	1, 10 mg/L (~0.5×10^5–4×10^5,~ 0.7×10^5–1.5×10^5 items/L)	96 h	Microplastic exposure lead to microplastic-specific impacts on corals; this species is more sensitive to PVC than LDPE; PVC microplastics (10 mg/L) cause high coral adhesion and oxidative stress, but increase photosynthetic efficiency and not induce energetic costs	(Rocha et al., 2020)
Mushroom coral (*Danafungia scruposa*)	Virgin PE microbeads; biofouled PE and PP fragments collected from Great Pacific Garbage Patch	212–355, 600–710, 850–1000 μm microbeads; 200–500, 500–800, 800–1000 μm fragments	2996 ± 5 beads/1.5 L bag; 2997 ± 6 beads/1.5 L bag, 3005 ± 35 biofouled fragments/1.5 L bag, 1480 ± 11 beads+1506 ± 14 biofouled fragments/1.5 L bag	2 days	Interaction between corals and microplastics through active ingestion and passive adhesion to coral surfaces; passive adhesion is the primary mechanism; coral ingest and retain more biofouled microplastics	(Corona et al., 2020)
Orange stony scleractinian coral (*Astroides calycularis*)	PE obtained from plastic bags	2–3 mm	20 items	30 min; 30 min; 90 min	Lack of identification mechanisms to distinguish between microplastics and food euphausiid shrimps; polyps spend considerate time for catching, swallowing, and regurgitating microplastics; Impair coral feeding performance and not gain enough energy from plankton feeding	(Savinelli et al., 2020)
Scleractinian coral (*Acropora tenuis*)	PE microbeads; weathered PP collected from beach	1, 6 μm PE microbeads; 0.5, 1, 2 mm^2 weathered PP	25–200 microbeads/L; 5–50 pieces/L	2.5 h; 24 h	Cause limited impacts on coral fertilization, embryo abnormality and larval settlement; not substantially interfere with the success of critical early life coral processes	(Berry et al., 2019)
Scleractinian corals (Acroporidae *Acropora muricata*, Pocilloporidae *Pocillopora verrucosa*, Poritidae *Porites lutea*, Helioporidae *Heliopora coerulea*)	HDPE	65–410 μm	0.25 mg/L (200 items/L)	6 months	Microplastic exposure lead to species-specific impacts on coral growth rates and health signs (e.g., bleaching, tissue necrosis, parasites); alter photosynthetic performance of symbionts; not change symbiont densities and chlorophyll concentrations	(Reichert et al., 2019)
Cold-water corals (*Lophelia pertusa*, *Madrepora oculata*)	LDPE (with the natural formation of surface microbial biofilm pre-incubated for two months)	10 × 10 cm PE macroplastics; 500 μm microbeads	--; 350 items/L	5 months	Species-specific impacts on two corals; microplastic exposure impair prey capture and growth rates of coral *Lophelia pertusa*, macroplastic films cause the polyp "cap" structure overgrows; plastic exposure do not affect growth and feeding of coral *Madrepora oculata*	(Mouchi et al., 2019)
Staghorn coral (*Acropora formosa*)	LDPE	<100, 100–200, 200–500 μm	0.05, 0.1 and 0.15 g/L	14 days	Microplastic exposure adversely affect coral health (bleaching and necrosis) with the dose- and size-dependent effects; complex process of microplastic ingestion and egestion; significantly release zooxanthellae	(Syakti et al., 2019)
Temperate northern star coral (*Astrangia poculata*)	Blue PE microbeads (with the formation of surface microbial biofilm incubated for 4–8 h; pre-spiked in the *Escherichia coli* cell cultures for 9 days)	170.5–230.8 μm	0.2 g/L; 10–25 microbeads with the *Escherichia coli* biofilm	90 min (feeding) +24 h (recovery in clean seawater); 4 weeks (*E. coli* biofilm-microbead feeding)	An average of 112 microplastic items/per polyp in wild-collected corals from Rhode Island; Ingested microplastics retain in the mesenterial tissues of the gastrovascular cavity, but majority of microbeads were expelled for 24 h; corals prefer to ingest microbeads and decline subsequent feeding of brine shrimp eggs; co-ingestion microbeads with *Escherichia coli* cells lead to coral death after 4 weeks	(Rotjan et al., 2019)
Small polyp scleractinian coral (*Pocillopora damicornis*)	PS	1 μm	50 mg/L (9×10^{10} items/L)	24 h	No significant impacts of symbiotic zooxanthellae density; observably increase chlorophyll content at	(Tang et al., 2018)

					12 h; acute exposure of microplastics enhance stress response and activities of antioxidant enzymes; suppress detoxification and immune capacities	
Cold-water coral (*Lophelia pertusa*)	LDPE (with the natural formation of surface microbial biofilm pre-incubated for two months)	10 × 10 cm LDPE macroplastics; 500 μm microbeads	--; 350 items/L	2 months	Micro- and macroplastics significantly decrease coral skeletal growth rates; Macroplastics increase polyp activity but reduce prey capture rates; microplastics not affect polyp behavior and prey capture rates, but reduce calcification	(Chapron et al., 2018)
Polyp scleractinian corals (*Montastraea cavernosa, Orbicella faveolata*)	PE microbeads (with the natural formation of surface microbial biofilm pre-incubated for six weeks); Polyester microfibers	PE (90–106 μm, 212–250 μm, 425–500 μm, 850–1000 μm, 1.7–2.0 mm, 2.4–2.8 mm); Polyester (3–5 mm)	30 mg/L	48 h	Majority of microbeads were expelled for 48 h; no calcification effects; no difference in ingestion or retention times of 425–500 μm microbeads versus 3–5 mm microfibers	(Hankins et al., 2018)
Six small polyp scleractinian coral species (*Acropora humilis, Acropora millepora, Pocillopora verrucosa, Pocillopora damicornis, Porites lutea, Porites cylindrica*)	Pristine PE (with the natural formation of surface microbial biofilm during exposure periods)	37–163 μm	4000 items/L	4 weeks	Different coral species respond differently to PE microplastics (e.g., microplastic ingestion and egestion, interaction with tentacles or mesenterial filaments, mucus production, overgrowth); cause negative health effects (e.g., bleaching and tissue necrosis)	(Reichert et al., 2018)
Scleractinian coral (*Astrangia poculata*)	Microbe-free plastic mixtures (including HDPE,LDPE,PP,PET,PC,PVC,PS); Sunlight-weathered and biofouled plastic mixtures (including PS, LDPE,HDPE)	500–1000 μm; 125–1000 μm	–	24 h	Ingestion of different plastic types by corals due to the plastic leachates as phagostimulants; corals ingest more microbe-free microplastics than the biofouled microplastics; retain ~8% of ingested plastics for >24 h	(Allen et al., 2017)
Mound-shaped stony scleractinian coral (*Dipsastrea pallida*)	Blue PP	10–2000 μm	0.395 g/L; 0.197 and 0.24 g/L	48 h; 12 and 3 h	Mistake microplastics for prey; ingested microplastics retain in the mesenterial tissue of coral gut cavity for >24 h	(Hall et al., 2015)
Scleractinian coral (*Stylophora pistillata*)	Beach-collected foam PS containing brominated flame retardant hexabromocyclododecanes (HBCDD)	Leachate from 0.6 g/L 0.5-1 mm cubic fragments (sliced from >2 cm beach-collected macrodebris) for 21 days	Leachate spiked with α-, β-, and γ-HBCDD	5 days	Beach-collected foam PS fragments leach 150 ng/g/day of ΣHBCDD; HBCDD bioaccumulation in coral tissues has limited impacts on coral photosynthetic performance, symbiont density and chlorophyll concentration; another constituent in leachate result in coral polyp retraction	(Aminot et al., 2020)
Symbiodiniaceae algae (*Cladocopium goreaui*) inhabiting in scleractinian corals	PS	1 μm	5 mg/L (9.0 × 10^9 items/L)	7 days	Microplastic exposure inhibit the growth and density of algae; significantly increase chlorophyll at 7 days and not change photochemical efficiency; suppress detoxification activity, nutrient uptake and photosynthetic performance; increase oxidative stress, apoptosis level and ion transport	(Su et al., 2020)
Coral (*Seriotopora caliendrum*); Sea anemone (*Aiptasia*) as an anthozoan model organism	PS	3, 6 μm	–	30 h	Bleached corals are likely to ingest and retain microplastics more easily than the healthy corals; microplastics move to mesenterial filament and then disperse throughout the body and tentacles; endodermal cells would catch and phagocytose microplastics; microplastics occupy the tentacle cell layer inhabited by symbionts *Symbiodiniaceae* and disturb normal coral-symbiont relationships.	(Okubo et al., 2020)
Stony scleractinian coral (*Favites chinensis*); sea anemone (*Aiptasia sp.*)	Fluorescent carboxylate microspheres; microbeads from commercial facewash	3, 6, 11 μm; 3–60 μm	–	2 days; 9 days	The ingestion of microplastics and *Artemia nauplii* with microsplastics severely suppress infectivity of symbiotic algae into the host; affect the initiation of symbiotic relationships	(Okubo et al., 2018)
Scleractinian corals (*Montipora capitata*, *Pocillopora damicornis*)	PE microbeads	150–180 μm	2000 items/L under 27 °C or increased 30 °C	10 days	Two coral species significantly decrease feeding on *Artemia nauplii* but not reduce microplastic ingestion under thermal stress	(Axworthy and Padilla-Gamiño, 2019)

microplastic ingestion by corals. Interestingly, Allen et al. (2017) found that the microbe-free, sunlight-weathered and biofouled microplastics were ingested by scleractinian corals due to the plastic leachate as phagostimulants. Corals would like to ingest the microbe-free microplastics than the plastics with a microbial biofilm, while this result is contrary to other microplastic feeding studies (Goss et al., 2018; Vroom et al., 2017). Recently, Corona et al. (2020) revealed that the probability of ingesting and retaining PE biofouled-microplastics by mushroom corals *Danafungia scruposa* was higher because corals may mistake the plastics spiked with microbial surface biofilms as the natural food source. It remains to be further studied whether the microplastic weathered/aging behaviors (e.g., UV-radiation, biofilm) play a role in plastic ingestion by diverse corals and cause other adverse impacts (e.g., intestinal blockage, transfer of pathogens and associated chemical contaminants). In addition, Reichert et al. (2018) investigated the response of six small polyp coral species to PE microplastics (37–163 μm, 4000 items/L) with a microbial biofilm, and found that the exposure to biofouled microplastics caused different impacts (e.g., microplastic ingestion and egestion, interaction with tentacles or mesenterial filaments, mucus production, overgrowth) on different coral species (Fig. 2a). The microplastics-coral interaction is not only the ingestion versus egestion processes, but also involves the complex pattern (Reichert et al., 2018; Syakti et al., 2019). Additionally, a recent study reported that orange stony scleractinian coral *Astroides calycularis* is lack of identification mechanisms to distinguish between microplastics and natural food euphausiid shrimps, and the presence of foods can stimulate ingestion of 2–3 mm PE microplastics (Savinelli et al., 2020). Also, coral polyps spent considerate time for treating microplastics, and these ingested microplastics impaired coral feeding performance. On the other hand, the amount comparison between microplastic consumption by corals and heterotrophic feeding is needed. Hall et al. (2015) found that ingestion rates of 10–2000 μm PP microplastics were similar to the consumption of plankton and *Artemia* nauplii. Another study done by Rotjan et al. (2019) reported that corals *Astrangia poculata* would prefer to ingest PE microbeads (170.5–230.8 μm), and reduce the intake of natural food brine shrimp eggs due to the false perception of "satiety", suggesting the inhibition of heterotrophic feeding caused by microplastic ingestion and potential coral health impacts (Fig. 2b). Nevertheless, evidence also showed that coral heterotrophic feeding rates can be far beyond microplastic consumption and not impaired by microplastic exposure (Corona et al., 2020; Martin et al., 2019).

In addition to the microplastic active ingestion by corals, the passive adhesion to the coral structure surface might be the primary microplastics-coral mechanisms (Corona et al., 2020; Martin et al., 2019), as shown in Fig. 2c. Nearly five years, laboratory studies have demonstrated that microplastic exposure (including active ingestion and passive surface adhesion) can influence the coral energetics, growth and health, with consequences for feeding behavior, photosynthetic performance, energy expenditure, skeletal calcification, and even tissue bleaching and necrosis (Table 2). Since 2018, Dr. Jessica Reichert and her co-workers reported that the species-specific impacts of microplastics on different scleractinian coral species. In their first experiments for four weeks, results showed six small polyp coral species (*Acropora humilis, Acropora millepora, Pocillopora verrucosa, Pocillopora damicornis, Porites lutea, Porites cylindrica*) responded differently to PE microplastics (37-163 μm, 4000 items/L) spiked with a microbial biofilm, and caused bleaching and tissue necrosis (Reichert et al., 2018). Then, they investigated the six months exposure of 65–410 μm PE microplastics (200 items/L) to four representative reef-building scleractinian corals in Indo-Pacific, and found that microplastics led to the species-specific effects on coral growth rates and health signs (e.g., bleaching, tissue necrosis, parasites) and altered the photosynthetic performance of symbionts (Reichert et al., 2019). Similarly, Mouchi et al. (2019) reported that PE microplastic exposure for five months had a species-specific impacts on two cold-water corals (*Lophelia pertusa* and

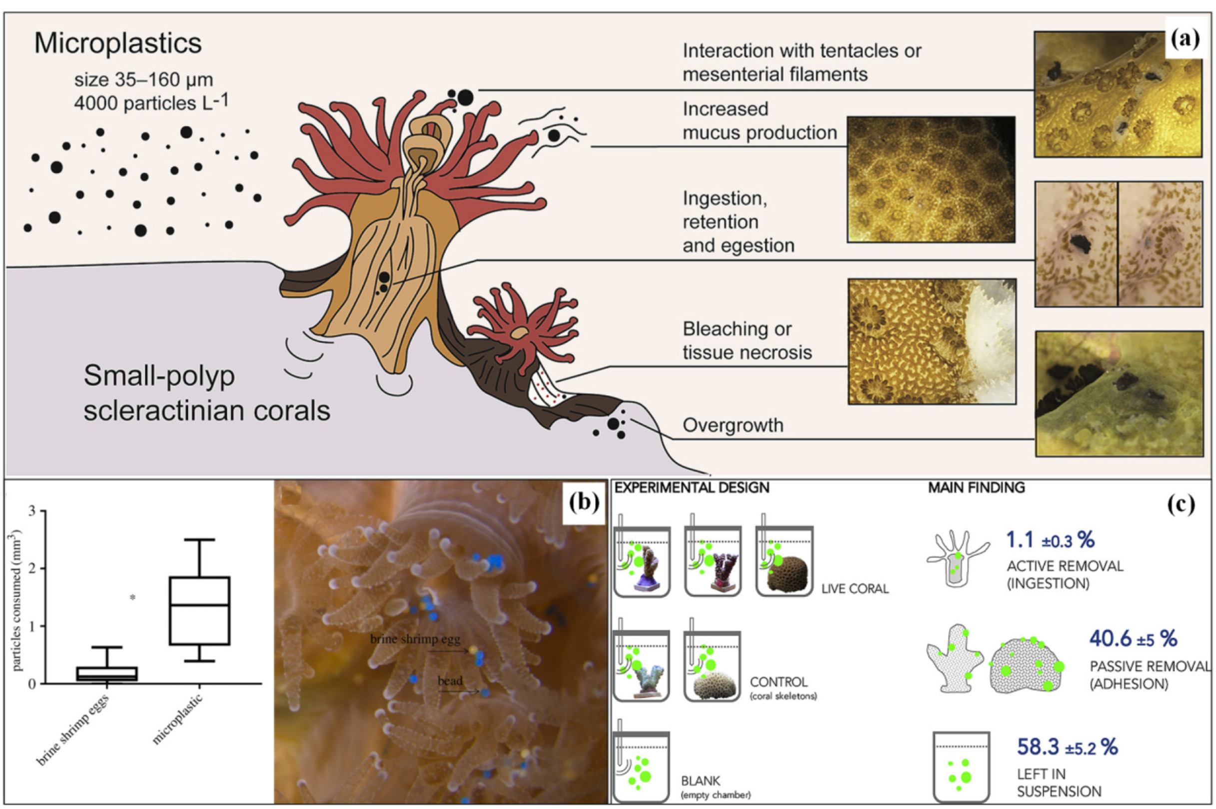

Fig. 2. The effects of microplastic ingestion and exposure on corals. **(a)** Response of scleractinian coral species to PE microplastics exposure. Reproduced with permission from Reichert et al. (2018). Copyright 2018 Elsevier. **(b)** Comparison between microplastic consumption by corals and heterotrophic feeding. Reproduced with permission from Rotjan et al. (2019). Copyright 2019 The Royal Society. **(c)** Microplastic active ingestion by corals and passive adhesion to coral surface. Reproduced with permission from Martin et al. (2019). Copyright 2019 Elsevier.

Madrepora oculata), and contrasted the difference in effects of the 10 × 10 cm PE macroplastic films and 500 μm PE microbeads. In their experiments, the exposure of PE microbeads at a concentration of 350 items/L impaired prey capture ability and growth rates of coral *Lophelia pertusa* but did not affect another coral *Madrepora oculata*. Notably, the exposure to PE macroplastics films had a limited effect on coral *Lophelia pertusa* and only caused the polyp "cap" structure overgrows due to the avoidance behavior of plastic obstacle and easy access to foods. Another study by Chapron et al. (2018) has reported that the two months exposure of 10 × 10 cm LDPE macroplastics and 500 μm LDPE microbeads significantly decreased the skeletal growth rates of cold-water coral *Lophelia pertusa*. Based on their results, macroplastic pieces from plastic bags increased polyp activity but reduced prey capture rates, while microplastic exposure did not influence polyp behavior and capture rates but decreased coral calcification. Noteworthy, Tang et al. (2018) studied the 24 h acute exposure of 1 μm PS microplastics (9×10^{10} items/L) to the cytological, physiological, and molecular responses of small polyp scleractinian coral *Pocillopora damicornis*. Their results revealed that acute exposure of microplastics enhanced stress response and activities of antioxidant enzymes, and suppressed detoxification and immune capacities. Additionally, Syakti et al. (2019) explored the effects of three microplastic sizes (<100, 100–200 and 200–500 μm) and concentrations (0.05, 0.1 and 0.15 g/L) on health of staghorn coral *Acropora formosa*. In their experiments for 14 days, they observed that LDPE microplastics exposure caused the coral bleaching and necrosis with the dose- and size-dependent effects. Finally, LDPE microplastics with a 100 μm size and concentration of 0.15 g/L led to the 93.6 ± 2.0% of bleaching and 5.9 ± 2.5% of necrosis, suggesting the adverse impact on coral health. Compared the potential effects induced by two types of microplastics (63–125 μm, 1 and 10 mg/L) for 96 h exposure, Rocha et al. (2020) revealed that hexacorallia coral *Zoanthus sociatus* was more susceptible to PVC microplastics than the LDPE. The exposure of PVC microplastics at a concentration of 10 mg/L significantly increased the plastic adhesion to coral surface and induced oxidative stress (e.g., lipid peroxidation, antioxidant defense), but it promoted the photosynthetic efficiency of symbionts and did not induce energetic costs. Recently, Lanctôt et al. (2020) investigated the four weeks exposure of 106–125 μm PE microplastics (5000 and 50,000 items/L) to scleractinian coral *Stylophora pistillata*, and found that PE microplastics at 50000 items/L adversely affected the photosynthetic efficiency in coral symbionts and both concentrations significantly altered the coral metabolite profiles. Taken together with their experimental results and previous studies, they concluded that microplastic exposure can disrupt host-symbiont relationship by the chemical signals.

However, the limited harms of microplastics to corals were also reported. For example, Hankins et al. (2018) found no observable effects on coral calcification for 48 h exposure to the biofouling PE microbeads (90–106, 425–500, and 850–1000 μm) at a concentration of 30 mg/L. In addition, Berry et al. (2019) studied whether the exposure to PE microbeads (1 and 6 μm) and beach-collected weathered PP microplastics (0.5, 1, and 2 mm^2) affects the early life processes of scleractinian coral *Acropora tenuis*. Results showed that only 2 mm^2 PP microplastics negatively influenced the coral fertilization, but other microplastic exposure had no significant impacts on the coral embryo development and larval settlement, suggesting the limited impacts on the coral early physiological stages. Furthermore, the species-specific and microplastic-specific responses of different coral species to microplastic exposure are required to pay more attention (Mouchi et al., 2019; Reichert et al., 2019; Rocha et al., 2020). As a result, the response of corals to microplastic exposure might be affected by some consequences, such as coral species and physiological stage, microplastic properties (e.g., polymer types, size, concentration, weathered behavior), and exposure conditions (e.g, duration, environmental stresses).

In general, the existing studies mainly focus on laboratory experiments at the higher microplastic concentrations than in-situ conditions in reef regions. Future efforts should be used the environmentally-realistic conditions (e.g., concentration, polymer type, weathered behavior) to perform the comprehensive evaluation regarding the long-term impacts of microplastic exposure on diverse coral species, especially the reef-building corals. Furthermore, the response mechanisms of corals to microplastic exposure (including active ingestion and passive surface adhesion) remain unclear and further explored. Noteworthy, the issue regarding which one of both microplastic active ingestion and passive surface adhesion causes greater impacts on coral species also needs to concern. Additionally, researchers must raise questions about the combined impacts of microplastics and other exogenous stressors (e.g., chemical pollutants, pathogens, climate-induced changes) on the highly biodiverse and complicated coral reef ecosystems.

4.2. Combined effects of microplastics and associated contaminants

Microplastics serve as a considerable sink and source of associated chemical contaminants and enhance their transport into organisms (Teuten et al., 2007; Teuten et al., 2009), potentially posing a threat to coral health. The field studies regarding the interaction between microplastics and associated contaminants in coral reef areas are presented in Table 3. On the one hand, microplastics can accumulate various environmental chemical contaminants such as PCBs, PAHs, DDTs and heavy metals, and carry them long distance (Brennecke et al., 2016; Godoy et al., 2019; Wang et al., 2018). Based on the metal analysis and PCBs determination, Hong et al. (2013) reported the presence of PCBs at ng/g levels and metals at the mg/kg in the coral reef bed sediments from Katen and Samui Island, Thailand. In subsequent experiments, they found that eight plastic materials can release PCBs at the variable concentrations for 6 months, suggesting the importance of selecting submerged plastic equipment with low additive leaching. More recently, Patterson et al. (2020) investigated the pollution status of different microplastics and heavy metals (Ni, Fe, Cr, Mn, Cu, Hg, Cd, Zn, Pb) in the Tuticorin and Vembar island groups of Gulf of Mannar from Indian Ocean reef regions. Based on the SEM-EDAX analysis and determination of ICP-MS and AAS, heavy metals associated with microplastics were greater than those in sediments at the mean μg/g levels, suggesting that microplastics can be served as a source of metals or that metals in sediments is preferentially distributed to microplastics. It is unknown whether microplastics transport enough environmental chemicals to corals and lead to substantial harm.

On the other hand, the fragmentation processes of plastic debris potentially release toxic additives such as plasticizers, flame retardants, and heavy metals that are added to plastics during manufacturing. According to the microplastic determination and PAEs analysis, Saliu et al. (2019) preliminarily reported that the possible correlation between microplastic contamination in seawater and plasticizer additive PAEs in scleractinian corals at the Faafu Atoll, Maldives. Then, based on the procedure combined the biocompatible solid-phase microextraction with liquid chromatography coupled to mass spectrometry, they developed a novel method for determining different PAEs in marine invertebrates (e.g., scleractinian corals, sponges, clams) (Saliu et al., 2020). Subsequently, Montano et al. (2020) investigated five PAEs in the coral reefs from Magoodhoo Island in Faafu Atoll by the LC-MS/MS analysis. Results showed that more than 95% of wild-collected scleractinian corals were polluted by the total PAEs, with an average concentration of 30 ng/g per coral. Alarmingly, a recent study showed how PS foam debris from beaches leach 150 ng/g/day flame-retardant hexabromocyclododecanes and their bioaccumulation in scleractinian corals, as well as how PS leachate affect coral physiology (e.g., photosynthetic performance, symbiont density, chlorophyll concentration, coral polyp retraction) in the short-term (Aminot et al., 2020).

From the above, the current studies provide limited data on the pollution status of plastic-derived associated chemical contaminants

Table 3
Field studies about interaction between microplastics and associated chemical contaminants in coral reef regions.

Investigation regions	Media	Contaminants	Analytical methods	Results	Ref.
Tuticorin and Vembar island groups in Gulf of Mannar, India	Sediment; Microplastic surface	Microplastics; Heavy metals	SEM-EDAX; ICP-MS (for MPs from sediments) and AAS (for sediments); Calculation of pollution indices	EDAX-analysis showed the presence of Ni, Cd, Pb, Cu, Al, Zn and Fe associated with microplastics; Heavy metal associated with microplastics were greater than those in sediments, suggesting microplastics as a source of metal pollution or metals from the sediment preferentially partition to microplastics.	(Patterson et al., 2020)
Faafu Atoll, Maldives	Scleractinian corals *Acropora muricata*; Neuston in subsurface seawater	Microplastics; Plastic additives PAEs	Microplastic determination; PAEs analysis by LC-MS	Widespread microplastic contamination and appreciable levels of PAEs in the scleractinian corals sampled inside the atoll were correlated with the highest microplastic concentration.	(Saliu et al., 2019)
Magoodhoo Island of Faafu Atoll, Maldives	Scleractinian corals (*Porites lutea*, *Pocillopora verrucosa* and *Pavona varians*)	Plastic additives- five PAEs	PAEs analysis by LC-MS/MS	More than 95% of scleractinian corals were contaminated, with a maximum of 172.4 ng/g; The average total PAEs concentration was about 30 ng/g per coral, but it in species, depth or reef exposure had no significant differences.	(Montano et al., 2020)
Samui and Katen coral reefs in Gulf of Thailand	Sediment	Plastic-derived metals and PCBs	Metal analysis; PCBs determination by gas chromatograph; Determination of PCBs release from plastic debris	Relatively little contamination of metals and PCBs in sediment of coral reef areas in the Gulf of Thailand; laboratory leaching study indicated that scientific equipment made of plastic materials might release PCBs to seawater and sediment.	(Hong et al., 2013)

(e.g., organic pollutants, heavy metals, toxic plastic additives) and establish a preliminary correlation between microplastic pollution and chemical pollution. Microplastics might be non-negligible sources and media to transport chemical pollution in the coral reef systems, where microplastic exposure or ingestion by corals potential result in the exposure to associated contaminants. However, determining how much heavy metals and toxic components transported into corals and whether contamination levels in environmental media (e.g., seawater, sediment) affect the transfer process remain unknown. Moreover, as these contaminants are present in relatively low concentrations in the environmental samples and easily influenced by external factors (e.g., coral species, sediment media, laboratory contamination), there is lack of a standard and accurate analytical method to identify and quantify them. Consequently, future efforts are required to investigate the pollution status of associated chemical contaminants in coral reefs, and explore their actual combined impacts with microplastics on various coral species.

4.3. Disease induced by microplastics

Plastic debris, which provides a durable, mobile and hydrophobic substrate, enhances the microbial colonization and biofilm formation. The "Plastisphere" comprises a variety of colonized microbial communities including heterotrophs, autotrophs, predators, and symbionts on plastic debris, potentially promoting the dispersal of harmful opportunistic pathogens (Amaral-Zettler et al., 2020; Zettler et al., 2013). According to a previous study, benthic macroplastics (>50 mm in diameter) significantly magnify the coral disease susceptibility and adversely influence the structurally-complex coral communities (Lamb et al., 2018). By comparison, due to its microscopic and surface properties, ubiquity, mobility, and complex interaction (e.g., ingestion, surface adhesion) with corals, microplastics might be easier to introduce disease-causing pathogens to invade coral reefs and increase the likelihood of disease susceptibility. Nevertheless, the potential mechanisms of microplastics on harmful microbial colonization, pathogen transmission and disease process, and their "pathogen-carrier" effects to corals remain to be further investigated.

In several previous studies, cross-ocean plastic debris (e.g., PP, PE) can act as colonization vectors for microbes, such as the genus *Vibrio*, *Rhodobacterales* and *Halofolliculina* spp. that are considered as the opportunistic pathogens associated with outbreaks of prevalent coral diseases including white syndromes and skeletal eroding band (Dang et al., 2008; Goldstein et al., 2014; Zettler et al., 2013). Recently, Feng et al. (2020) placed nine kinds of 3–5 mm microplastics (including PP, PS, PC, PA, PVC, LDPE, PET, EPS, ABS) in four coral reef sites for two weeks, and investigated the composition and properties of microplastic surface biofilms. Based on their colonization experiments, the sequencing results of 16S rRNA revealed that the composition and distribution of biofilm on microplastic surface in coral reef area remarkably differed from the surrounding seawater samples, and were mainly affected by the polymer types of microplastics and reef sites. Noteworthy, the dominant biofilm pathogens inhabiting in microplastics include *Vibrionaceae*, *Rhodobacteraceae* and *Flavobacteraceae*, and *Vibrio*, which can result in tissue damage and coral albinism, respectively. Also, other pathogens such as *Pseudomonas* and *Bbellvibrio cholerae* were observed in these microplastic biofilms. Additionally, Rotjan et al. (2019) studied the ingestion of PE microbeads (170.5–230.8 μm) with the *Escherichia coli* biofilm by a temperate coral *Astrangia poculata*, and found that increased *Escherichia coli* on the polyps were observed within two weeks and coral polyps died after four weeks post-ingestion. On the other hand, evidence showed that the short-term exposure to 1.0 μm PS microplastics (9×10^{10} items/L) repressed the detoxification and immune system of the scleractinian coral *Pocillopora damicornis* (Tang et al., 2018), which might increase the likelihood of coral disease susceptibility. These limited studies indicated the non-negligible threat of disease-causing pathogens inhabiting in microplastic surface and provided a new research direction about the impacts of "Plastisphere" communities on diverse corals.

4.4. Impacts of microplastics on coral-zooxanthellae symbiosis

Reef-building coral species gain the majority of nutrient and energy from the endosymbiotic relationship with the photosynthetic genus *Symbiodiniacea*, thus the sustainable coral-zooxanthellae symbiosis is the cornerstone of healthy coral reef ecosystems. So far, the impacts of microplastics on the coral-zooxanthellae symbiosis and photosynthetic performance have been rarely reported. The first evidence demonstrated that the direct or indirect ingestion of carboxylate microspheres (3, 6, 11 μm) and microbeads from commercial facewash (3–60 μm) can severely inhibit the symbiotic *Symbiodiniacea* infecting into their host (e.g., coral *Favites chinensis*, sea anemone *Aiptasia sp.*), disturbing their initiation of symbiotic relationship (Okubo et al., 2018). Then, they reported that PS microplastics (3 and 6 μm) can be accumulated in the zone of phagocytosis and endocytosed into the cells of mesenterial filaments (Okubo et al., 2020). These microplastics might be dispersed in the cell layer of coral tentacles and occupy the sites inhabited by

Symbiodiniaceae, thus hindering normal coral-symbionts relationships. Moreover, the exposure to 1 μm PS microplastics (9.0×10^9 items/L) suppressed the growth of endosymbiotic *Symbiodiniaceae* species by affecting its apoptosis and metabolism, declining the detoxification activity and photosynthesis, and increasing oxidative stress and apoptosis (Su et al., 2020). Another study done by Syakti et al. (2019) found that the ingestion of LDPE microplastics (<100, 100–200, and 200–500 μm) by staghorn coral *Acropora Formosa* led to the release of zooxanthellae and subsequent coral bleaching and necrosis. Currently, Lanctôt et al. (2020) reported that the four weeks exposure of PE microplastics (106–125 μm, 50,000 items/L) negatively affected photosynthetic efficiency of symbionts in the scleractinian coral *Stylophora pistillata* and significantly altered their metabolite profiles. These authors thought that microplastics can disrupt the host-symbiont physiological relationships. Somewhat differently, Reichert et al. (2019) stated that six months exposure to HDPE microplastics (65–410 μm, 200 items/L) resulted in the species-specific impacts (including enhancement or no change) on the photosynthetic performance of four scleractinian coral species, but it did not change the symbiont densities and chlorophyll contents. Although the 24 h acute exposure to 1 μm PS microplastics (9×10^{10} items/L) led to the adverse cytological, physiological, and molecular responses to the scleractinian coral *Pocillopora damicornis*, the increase of symbiont density and chlorophyll content was observed (Tang et al., 2018). Additionally, Rocha et al. (2020) reported that 10 mg/L PVC microplastics (63–125 μm) exposed to the Hexacorallia coral *Zoanthus sociatus* for 96 h increased the photosynthetic efficiency and did not induce the energetic costs. From the above, additional evidence must to be gained to assess whether the enough adverse impacts of microplastics on the coral-zooxanthellae symbiosis in the long-term exposure.

4.5. Potential threats to coral reef systems

Coral reefs are the crucial marine regions with the high complexity, biodiversity and productivity, but in turn, they are exposed to the combination between natural perturbations and human activities. Different influence factors such as climate change, ocean acidification, marine pollution, diseases and plastic pollution affect coral reefs in a different way. Notably, the mutual combination of factors potentially leads to the greater impacts than a single factor alone. For example, complex interactions between nano- or micro-plastics and climate change may affect coral reef systems in the long term. Recent evidence showed that the coupled impacts between the environmental parameters (e.g., CO_2, temperature, light irradiance) shifted by climate change and PS nanoplastics (100 nm) can influence the growth of primary producer microalgae and change toxicity of nanoplastics (Yang et al., 2020). The first study by Axworthy and Padilla-Gamiño (2019) into the effect of marine thermal stress on the microplastic ingestion and heterotrophic feeding by two scleractinian corals (*Montipora capitate* and *Pocillopora damicornis*) found that rising sea temperatures (30 °C) did not significantly affect microplastics ingestion, but observably reduced heterotrophic feeding of *Artemia nauplii*. Furthermore, Okubo et al. (2020) reported that bleached corals *Seriatopora caliendrum* under thermal stress are more likely to ingest and retain microplastics (3 and 6 μm) than the healthy corals. To better comprehend microplastics as an emerging global pollutants, exploring the potential synergistic effects of microplastics with environmental stressors relevant to climate change on reef-building corals is urgently needed.

5. Conclusions and recommendations

Considering the ecological and economic value of coral reef systems, microplastic pollution in reef regions is gradually receiving attention. In recent years, studies have demonstrated that microplastics have been detected in different compartments (e.g., seawater, sediment, corals, aquatic biota) of coral reef regions in the Southeast Asia, Pacific, Australia, Indian Ocean and Atlantic. Nevertheless, there is a significant difference in the abundance and distribution characteristics of microplastics, which might be primarily attributed to intensive anthropogenic activities (e.g., population density, fishery activities, human domestic sewage, land-based emissions, tourist activities, etc.) and natural factors (e.g., fragmentation behaviors, water flow transport, sediment properties, habitat condition, atmospheric deposition, etc.). Furthermore, laboratory evidence showed that main interactions between microplastics and corals are microplastic active ingestion and passive surface adhesion. The exposure of microplastics to corals can adversely affect coral physiology, energetics, growth and health, and potentially lead to tissue bleaching and necrosis in the long-term exposure. Moreover, toxic chemicals and disease-causing pathogens onto the microplastic surface might increase the risks to coral health.

Although some efforts about the field survey and toxicity studies of microplastics have been performed, there are still many scientific issues that require to be addressed in future studies. Some points are listed as follows:

(1) Incorporate microplastics and plastic-derived associated contaminants into environmental monitoring indicators in coral reef regions and establish a long-term effective monitoring network to evaluate microplastic pollution status. Nevertheless, current analytical methods (including sampling, extraction, identification and qualification) of microplastics used in reef investigations have been not standardized. Further efforts are required to develop the standardized, operable and environmentally-friendly analytical methods, and clarify the microplastic pollution in different compartments (e.g., seawater, sediment, corals, aquatic biota) of coral reef regions. Notably, the level of PAEs in coral tissues may represent a meaningful indicator for microplastic pollution (Saliu et al., 2019). Meanwhile, the main sources, transport modes and accumulation areas of microplastics in coral reefs need to be identified.

(2) Evaluate the impacts of microplastics on coral species comprehensively. While present laboratory ecotoxicological studies revealed the short-term impacts on coral species at the relatively high microplastic concentrations, the additional evidence about long-term effects of microplastics and related toxic mechanisms under environmentally realistic conditions is urgently required. In addition, microplastics can serve as sinks and sources of environmental chemical pollutants (e.g., heavy metals, persistent organic pollutants, plastic additives), thus their potential combined effects on corals require further studied. Moreover, more attention should be paid to the underlying pathogenic mechanisms of corals and interference of normal host-symbiont relationships caused by microplastics exposure.

(3) Understand the potential impacts of nanoplastics. Due to its nanoscopic size and limitations of analytical techniques, the abundance and distribution of nanoplastics in coral reefs are still uninvestigated. Thus, the development of advanced and effective analytical techniques to improve the resolution and sensitivity of nanoplastics determination must be required in the future works (Li et al., 2020). In addition, the adverse effects of nanoplastics on corals should be further assessed because it may be more likely to interact with corals and its toxicological risks might increase with the decreasing plastic particle size.

(4) Explore the threat of nano/microplastics to coral reef systems. As an exogenetic contaminant, microplastics can widely distribute in the different media (e.g., surface water, water column and bottom sediment) in reef regions and interact with various aquatic biota (e.g., corals, fish, bivalves, etc.). To our knowledge, no data exist for the effects of microplastics on trophic structure and ecosystem function of coral reef systems. Also, study regarding synergistic effects of nano/microplastics with environmental stressors relevant to climate change on reef-building corals are still scarce.

With the rapid increasing plastic consumption and the pervasive global coral bleaching, marine microplastic research must focus on the critical coral reef areas and include a comprehensive knowledge about the distribution, fate, trophic transfer, and toxicological effects from an ecosystem perspective.

(5) Develop the protection strategy of coral reefs and reduce microplastic environmental emissions. Of even greater concern is that the removal of microplastics from the reef areas is extremely difficult and impractical. Nevertheless, annual global plastic production is still increasing rapidly year by year and has reached at least 359 Mt. in 2018 (PlasticsEurope, 2019). Consequently, future plastic researchers should concern how to reduce microplastic pollution from the root by reducing plastic consumption, improving waste management and eliminating the vast marine inputs of microplastics.

Declaration of competing interest

The authors declare no competing financial interest.

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References

Alimi, O.S., Farner Budarz, J., Hernandez, L.M., Tufenkji, N., 2018. Microplastics and nanoplastics in aquatic environments: aggregation, deposition, and enhanced contaminant transport. Environ. Sci. Technol. 52 (4), 1704–1724.

Allen, A.S., Seymour, A.C., Rittschof, D., 2017. Chemoreception drives plastic consumption in a hard coral. Mar. Pollut. Bull. 124 (1), 198–205.

Allen, S., Allen, D., Phoenix, V.R., Le Roux, G., Durántez Jiménez, P., Simonneau, A., et al., 2019. Atmospheric transport and deposition of microplastics in a remote mountain catchment. Nat. Geosci. 12 (5), 339–344.

Amaral-Zettler, L.A., Zettler, E.R., Mincer, T.J., 2020. Ecology of the plastisphere. Nat. Rev. Microbiol 18 (3), 139–151.

Aminot, Y., Lanctôt, C., Bednarz, V., Robson, W.J., Taylor, A., Ferrier-Pagès, C., et al., 2020. Leaching of flame-retardants from polystyrene debris: bioaccumulation and potential effects on coral. Mar. Pollut. Bull. 151, 110862.

Arthur, C., Baker, J.E., Bamford, H.A., 2009. Proceedings of the International Research Workshop on the Occurrence, Effects, and Fate of Microplastic Marine Debris, September 9–11, 2008. University of Washington Tacoma, Tacoma, WA, USA.

Axworthy, J.B., Padilla-Gamiño, J.L., 2019. Microplastics ingestion and heterotrophy in thermally stressed corals. Sci. Rep. 9 (1), 18193.

Bank, M.S., Hansson, S.V., 2019. The plastic cycle: a novel and holistic paradigm for the Anthropocene. Environ. Sci. Technol. 53 (13), 7177–7179.

Berry, K.L.E., Epstein, H.E., Lewis, P.J., Hall, N.M., Negri, A.P., 2019. Microplastic contamination has limited effects on coral fertilisation and larvae. Diversity 11 (12), 228.

Brahney, J., Hallerud, M., Heim, E., Hahnenberger, M., Sukumaran, S., 2020. Plastic rain in protected areas of the United States. Science 368 (6496), 1257.

Brennecke, D., Duarte, B., Paiva, F., Caçador, I., Canning-Clode, J., 2016. Microplastics as vector for heavy metal contamination from the marine environment. Estuar. Coast. Shelf Sci. 178, 189–195.

Burke, L., Reytar, K., Spalding, M., Perry, A., 2011. World Resources Institute, Reefs at Risk Revisited.

Carbery, M., O'Connor, W., Palanisami, T., 2018. Trophic transfer of microplastics and mixed contaminants in the marine food web and implications for human health. Environ. Int. 115, 400–409.

de Carvalho-Souza, G.F., Llope, M., Tinôco, M.S., Medeiros, D.V., Maia-Nogueira, R., Sampaio, C.L.S., 2018. Marine litter disrupts ecological processes in reef systems. Mar. Pollut. Bull. 133, 464–471.

Chapron, L., Peru, E., Engler, A., Ghiglione, J.F., Meistertzheim, A.L., Pruski, A.M., et al., 2018. Macro- and microplastics affect cold-water corals growth, feeding and behaviour. Sci. Rep. 8 (1), 15299.

Cheang, C.C., Ma, Y., Fok, L., 2018. Occurrence and composition of microplastics in the seabed sediments of the coral communities in proximity of a metropolitan area. Int. J. Env. Res. Public Health 15 (10).

Chen, C., Chen, L., Yao, Y., Artigas, F., Huang, Q., Zhang, W., 2019. Organotin release from polyvinyl chloride microplastics and concurrent photodegradation in water: impacts from salinity, dissolved organic matter, and light exposure. Environ. Sci. Technol. 53 (18), 10741–10752.

Connors, E.J., 2017. Distribution and biological implications of plastic pollution on the fringing reef of Mo'orea. French Polynesia. PeerJ 5, e3733.

Cordova, Muhammad R., H., T.A., Prayudha, Bayu, 2018. Occurrence and abundance of microplastics in coral reef sediment: a case study in Sekotong, Lombok-Indonesia. AES Bioflux 10 (1), 23–29.

Corona, E., Martin, C., Marasco, R., Duarte, C.M., 2020. Passive and active removal of marine microplastics by a mushroom coral (Danafungia scruposa). Front. Mar. Sci. 7 (128).

Dang, H., Li, T., Chen, M., Huang, G., 2008. Cross-Ocean distribution of *Rhodobacterales* bacteria as primary surface colonizers in temperate coastal marine waters. Appl. Environ. Microbiol. 74 (1), 52.

Dawson, A.L., Kawaguchi, S., King, C.K., Townsend, K.A., King, R., Huston, W.M., et al., 2018. Turning microplastics into nanoplastics through digestive fragmentation by Antarctic krill. Nat. Commun. 9 (1), 1001.

Ding, J., Jiang, F., Li, J., Wang, Z., Sun, C., Wang, Z., et al., 2019. Microplastics in the Coral Reef Systems from Xisha Islands of South China Sea. Environ. Sci. Technol 53 (14), 8036–8046.

Eerkes-Medrano, D., Thompson, R.C., Aldridge, D.C., 2015. Microplastics in freshwater systems: a review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. Water Res. 75, 63–82.

Feng, L., He, L., Jiang, S., Chen, J., Zhou, C., Qian, Z.-J., et al., 2020. Investigating the composition and distribution of microplastics surface biofilms in coral areas. Chemosphere 252, 126565.

Garnier, Y., Jacob, H., Guerra, A.S., Bertucci, F., Lecchini, D., 2019. Evaluation of microplastic ingestion by tropical fish from Moorea Island, French Polynesia. Mar. Pollut. Bull. 140, 165–170.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3 (7), e1700782.

Godoy, V., Blázquez, G., Calero, M., Quesada, L., Martín-Lara, M.A., 2019. The potential of microplastics as carriers of metals. Environ. Pollut. 255, 113363.

Goldstein, M.C., Carson, H.S., Eriksen, M., 2014. Relationship of diversity and habitat area in North Pacific plastic-associated rafting communities. Mar. Biol. 161 (6), 1441–1453.

González-Pleiter, M., Velázquez, D., Edo, C., Carretero, O., Gago, J., Barón-Sola, Á., et al., 2020. Fibers spreading worldwide: microplastics and other anthropogenic litter in an Arctic freshwater lake. Sci. Total Environ. 722, 137904.

Goss, H., Jaskiel, J., Rotjan, R., 2018. Thalassia testudinum as a potential vector for incorporating microplastics into benthic marine food webs. Mar. Pollut. Bull. 135, 1085–1089.

Hall, N.M., Berry, K.L.E., Rintoul, L., Hoogenboom, M.O., 2015. Microplastic ingestion by scleractinian corals. Mar. Biol. 162 (3), 725–732.

Hankins, C., Duffy, A., Drisco, K., 2018. Scleractinian coral microplastic ingestion: potential calcification effects, size limits, and retention. Mar. Pollut. Bull. 135, 587–593.

Hartmann, N.B., Huffer, T., Thompson, R.C., Hassellov, M., Verschoor, A., Daugaard, A.E., et al., 2019. Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris. Environ. Sci. Technol 53 (3), 1039–1047.

Hernandez, L.M., Xu, E.G., Larsson, H.C.E., Tahara, R., Maisuria, V.B., Tufenkji, N., 2019. Plastic teabags release billions of microparticles and nanoparticles into tea. Environ. Sci. Technol. 53 (21), 12300–12310.

Hidalgo-Ruz, V., Gutow, L., Thompson, R.C., Thiel, M., 2012. Microplastics in the marine environment: a review of the methods used for identification and quantification. Environ. Sci. Technol. 46 (6), 3060–3075.

Hoegh-Guldberg, O., Mumby, P.J., Hooten, A.J., Steneck, R.S., Greenfield, P., Gomez, E., et al., 2007. Coral reefs under rapid climate change and ocean acidification. Science 318 (5857), 1737.

Hong, G.H., Kim, C.J., Yeemin, T., Siringan, F.P., Zhang, J., Lee, H.M., et al., 2013. Potential release of PCBs from plastic scientific gear to fringing coral reef sediments in the Gulf of Thailand. Deep-Sea Res. II Top. Stud. Oceanogr. 96, 41–49.

Huang, Y., Yan, M., Xu, K., Nie, H., Gong, H., Wang, J., 2019. Distribution characteristics of microplastics in Zhubi Reef from South China Sea. Environ. Pollut. 255, 113133.

Hughes, T.P., Kerry, J.T., Baird, A.H., Connolly, S.R., Dietzel, A., Eakin, C.M., et al., 2018. Global warming transforms coral reef assemblages. Nature 556 (7702), 492–496.

Imhof, H.K., Sigl, R., Brauer, E., Feyl, S., Giesemann, P., Klink, S., et al., 2017. Spatial and temporal variation of macro-, meso- and microplastic abundance on a remote coral island of the Maldives, Indian Ocean. Mar. Pollut. Bull. 116 (1), 340–347.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., et al., 2015. Plastic waste inputs from land into the ocean. Science 347 (6223), 768.

Jensen, L.H., Motti, C.A., Garm, A.L., Tonin, H., Kroon, F.J., 2019. Sources, distribution and fate of microfibres on the Great Barrier Reef, Australia. Sci. Rep. 9 (1), 9021.

Kane, I.A., Clare, M.A., Miramontes, E., Wogelius, R., Rothwell, J.J., Garreau, P., et al., 2020. Seafloor microplastic hotspots controlled by deep-sea circulation. Science 368 (6495), 1140.

Koelmans, A.A., Besseling, E., Shim, W.J., 2015. Nanoplastics in the aquatic environment. Crit. Rev. 325–340.

Kroon, F.J., Motti, C.E., Jensen, L.H., Berry, K.L.E., 2018. Classification of marine microdebris: a review and case study on fish from the Great Barrier Reef, Australia. Sci. Rep. 8 (1), 16422.

Kroon, F.J., Berry, K.L.E., Brinkman, D.L., Kookana, R., Leusch, F.D.L., Melvin, S.D., et al., 2020. Sources, presence and potential effects of contaminants of emerging concern in the marine environments of the Great Barrier Reef and Torres Strait, Australia. Sci. Total Environ. 719, 135140.

La Beur, L., Henry, L.-A., Kazanidis, G., Hennige, S., McDonald, A., Shaver, M.P., et al., 2019. Baseline assessment of marine litter and microplastic ingestion by cold-water coral

reef benthos at the East Mingulay marine protected area (Sea of the Hebrides, Western Scotland). Front. Mar. Sci. 6 (80).
Lamb, J.B., Wenger, A.S., Devlin, M.J., Ceccarelli, D.M., Williamson, D.H., Willis, B.L., 2016. Reserves as tools for alleviating impacts of marine disease. Philosophical Transactions of the Royal Society B: Biological Sciences 371 (1689), 20150210.
Lamb, J.B., Willis, B.L., Fiorenza, E.A., Couch, C.S., Howard, R., Rader, D.N., et al., 2018. Plastic waste associated with disease on coral reefs. Science 359 (6374), 460.
Lanctôt, C.M., Bednarz, V.N., Melvin, S., Jacob, H., Oberhaensli, F., Swarzenski, P.W., et al., 2020. Physiological stress response of the scleractinian coral Stylophora pistillata exposed to polyethylene microplastics. Environ. Pollut. 263, 114559.
Law, K.L., Thompson, R.C., 2014. Microplastics in the seas. Science 345 (6193), 144.
Lebreton, L.C.M., van der Zwet, J., Damsteeg, J.W., Slat, B., Andrady, A., Reisser, J., 2017. River plastic emissions to the world's oceans. Nat. Commun. 8, 15611.
Li, J., Liu, H., Paul Chen, J., 2018. Microplastics in freshwater systems: a review on occurrence, environmental effects, and methods for microplastics detection. Water Res. 137, 362–374.
Li, P., Li, Q., Hao, Z., Yu, S., Liu, J., 2020. Analytical methods and environmental processes of nanoplastics. J. Environ. Sci. 94, 88–99.
Liu, K., Wu, T., Wang, X., Song, Z., Zong, C., Wei, N., et al., 2019a. Consistent transport of terrestrial microplastics to the ocean through atmosphere. Environ. Sci. Technol. 53 (18), 10612–10619.
Liu, X., Shi, H., Xie, B., Dionysiou, D.D., Zhao, Y., 2019b. Microplastics as both a sink and a source of Bisphenol A in the marine environment. Environ. Sci. Technol. 53 (17), 10188–10196.
Liu, P., Zhan, X., Wu, X., Li, J., Wang, H., Gao, S., 2020. Effect of weathering on environmental behavior of microplastics: properties, sorption and potential risks. Chemosphere 242, 125193.
Martin, C., Corona, E., Mahadik, G.A., Duarte, C.M., 2019. Adhesion to coral surface as a potential sink for marine microplastics. Environ. Pollut. 255, 113281.
Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., The, P.G., 2009. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. PLoS Med. 6 (7), e1000097.
Montano, S., Seveso, D., Maggioni, D., Galli, P., Corsarini, S., Saliu, F., 2020. Spatial variability of phthalates contamination in the reef-building corals Porites lutea, Pocillopora verrucosa and Pavona varians. Mar. Pollut. Bull. 155, 111117.
Mouchi, V., Chapron, L., Peru, E., Pruski, A.M., Meistertzheim, A.-L., Vétion, G., et al., 2019. Long-term aquaria study suggests species-specific responses of two cold-water corals to macro-and microplastics exposure. Environ. Pollut. 253, 322–329.
Nie, H., Wang, J., Xu, K., Huang, Y., Yan, M., 2019. Microplastic pollution in water and fish samples around Nanxun Reef in Nansha Islands, South China Sea. Sci. Total Environ. 696, 134022.
Okubo, N., Takahashi, S., Nakano, Y., 2018. Microplastics disturb the anthozoan-algae symbiotic relationship. Mar. Pollut. Bull. 135, 83–89.
Okubo, N., Tamura-Nakano, M., Watanabe, T., 2020. Experimental observation of microplastics invading the endoderm of anthozoan polyps. Mar. Environ. Res. 162, 105125.
Page, C.A., Willis, B.L., 2008. Epidemiology of skeletal eroding band on the Great Barrier Reef and the role of injury in the initiation of this widespread coral disease. Coral Reefs 27 (2), 257–272.
Patterson, J., Jeyasanta, K.I., Sathish, N., Edward, J.K.P., Booth, A.M., 2020. Microplastic and heavy metal distributions in an Indian coral reef ecosystem. Sci. Total Environ. 744, 140706.
Patti, T.B., Fobert, E.K., Reeves, S.E., Burke da Silva, K., 2020. Spatial distribution of microplastics around an inhabited coral island in the Maldives, Indian Ocean. Sci. Total Environ. 748, 141263.
PlasticsEurope, 2019. Plastics – The Facts 2019. An Analysis of European Latest Plastics Production, Demand and Waste Data.
Portz, L., Manzolli, R.P., Herrera, G.V., Garcia, L.L., Villate, D.A., Ivar do Sul, J.A., 2020. Marine litter arrived: distribution and potential sources on an unpopulated atoll in the Seaflower Biosphere Reserve, Caribbean Sea. Mar. Pollut. Bull. 157, 111323.
Reichert, J., Schellenberg, J., Schubert, P., Wilke, T., 2018. Responses of reef building corals to microplastic exposure. Environ. Pollut. 237, 955–960.
Reichert, J., Arnold, A.L., Hoogenboom, M.O., Schubert, P., Wilke, T., 2019. Impacts of microplastics on growth and health of hermatypic corals are species-specific. Environ. Pollut. 254, 113074.
Reisser, J., Shaw, J., Wilcox, C., Hardesty, B.D., Proietti, M., Thums, M., et al., 2013. Marine plastic pollution in waters around Australia: characteristics, concentrations, and pathways. PLoS One 8 (11), e80466.
Rillig, M.C., Lehmann, A., 2020. Microplastic in terrestrial ecosystems. Science 368 (6498), 1430.
Rocha, R.J.M., Rodrigues, A.C.M., Campos, D., Cícero, L.H., Costa, A.P.L., Silva, D.A.M., et al., 2020. Do microplastics affect the zoanthid Zoanthus sociatus? Sci. Total Environ. 713, 136659.
Rochman, C.M., 2018. Microplastics research—from sink to source. Science 360 (6384), 28.
Rochman, C.M., Hoellein, T., 2020. The global odyssey of plastic pollution. Science 368 (6496), 1184.
Rochman, C.M., Kross, S.M., Armstrong, J.B., Bogan, M.T., Darling, E.S., Green, S.J., et al., 2015. Scientific evidence supports a ban on microbeads. Environ. Sci. Technol 49 (18), 10759–10761.
Rochman, C.M., Brookson, C., Bikker, J., Djuric, N., Earn, A., Bucci, K., et al., 2019. Rethinking microplastics as a diverse contaminant suite. Environ. Toxicol. Chem. 38 (4), 703–711.
Rotjan, R.D., Sharp, K.H., Gauthier, A.E., Yelton, R., Lopez, E.M.B., Carilli, J., et al., 2019. Patterns, dynamics and consequences of microplastic ingestion by the temperate coral, Astrangia poculata. Proc. Biol. Sci. 286 (1905), 20190726.
Saliu, F., Montano, S., Garavaglia, M.G., Lasagni, M., Seveso, D., Galli, P., 2018. Microplastic and charred microplastic in the Faafu Atoll, Maldives. Mar. Pollut. Bull. 136, 464–471.
Saliu, F., Montano, S., Leoni, B., Lasagni, M., Galli, P., 2019. Microplastics as a threat to coral reef environments: detection of phthalate esters in neuston and scleractinian corals from the Faafu Atoll, Maldives. Mar. Pollut. Bull. 142, 234–241.
Saliu, F., Montano, S., Lasagni, M., Galli, P., 2020. Biocompatible solid-phase microextraction coupled to liquid chromatography triple quadrupole mass spectrometry analysis for the determination of phthalates in marine invertebrate. J. Chromatogr. 1618, 460852.
Savinelli, B., Vega Fernández, T., Galasso, N.M., D'Anna, G., Pipitone, C., Prada, F., et al., 2020. Microplastics impair the feeding performance of a Mediterranean habitat-forming coral. Mar. Environ. Res. 155, 104887.
Shen, M., Zhang, Y., Zhu, Y., Song, B., Zeng, G., Hu, D., et al., 2019. Recent advances in toxicological research of nanoplastics in the environment: a review. Environ. Pollut. 252, 511–521.
Shen, M., Huang, W., Chen, M., Song, B., Zeng, G., Zhang, Y., 2020. (Micro)plastic crisis: unignorable contribution to global greenhouse gas emissions and climate change. J. Clean. Prod. 254, 120138.
de Souza Machado, A.A., Kloas, W., Zarfl, C., Hempel, S., Rillig, M.C., 2018. Microplastics as an emerging threat to terrestrial ecosystems. Glob. Chang. Biol. 24 (4), 1405–1416.
Spalding, M.D., Brown, B.E., 2015. Warm-water coral reefs and climate change. Science 350 (6262), 769.
Su, Y., Zhang, K., Zhou, Z., Wang, J., Yang, X., Tang, J., et al., 2020. Microplastic exposure represses the growth of endosymbiotic dinoflagellate Cladocopium goreaui in culture through affecting its apoptosis and metabolism. Chemosphere 244, 125485.
Syakti, A.D., Jaya, J.V., Rahman, A., Hidayati, N.V., Raza'i, T.S., Idris, F., et al., 2019. Bleaching and necrosis of staghorn coral (Acropora formosa) in laboratory assays: immediate impact of LDPE microplastics. Chemosphere 228, 528–535.
Tan, F., Yang, H., Xu, X., Fang, Z., Xu, H., Shi, Q., et al., 2020. Microplastic pollution around remote uninhabited coral reefs of Nansha Islands, South China Sea. Sci. Total Environ. 725, 138383.
Tang, J., Ni, X., Zhou, Z., Wang, L., Lin, S., 2018. Acute microplastic exposure raises stress response and suppresses detoxification and immune capacities in the scleractinian coral Pocillopora damicornis. Environ. Pollut. 243, 66–74.
Teuten, E.L., Rowland, S.J., Galloway, T.S., Thompson, R.C., 2007. Potential for plastics to transport hydrophobic contaminants. Environ. Sci. Technol. 41 (22), 7759–7764.
Teuten, E.L., Saquing, J.M., Knappe, D.R.U., Barlaz, M.A., Jonsson, S., Björn, A., et al., 2009. Transport and release of chemicals from plastics to the environment and to wildlife. Philosophical Transactions of the Royal Society B: Biological Sciences 364 (1526), 2027–2045.
Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., et al., 2004. Lost at sea: where is all the plastic? Science 304 (5672), 838.
Vidyasakar, A., Neelavannan, K., Krishnakumar, S., Prabaharan, G., Sathiyabama Alias Priyanka, T., Magesh, N.S., et al., 2018. Macrodebris and microplastic distribution in the beaches of Rameswaram Coral Island, Gulf of Mannar, Southeast coast of India: a first report. Mar. Pollut. Bull. 137, 610–616.
Vroom, R.J.E., Koelmans, A.A., Besseling, E., Halsband, C., 2017. Aging of microplastics promotes their ingestion by marine zooplankton. Environ. Pollut. 231, 987–996.
Wang, F., Wong, C.S., Chen, D., Lu, X., Wang, F., Zeng, E.Y., 2018. Interaction of toxic chemicals with microplastics: a critical review. Water Res. 139, 208–219.
Wang, T., Zou, X., Li, B., Yao, Y., Zang, Z., Li, Y., et al., 2019. Preliminary study of the source apportionment and diversity of microplastics: taking floating microplastics in the South China Sea as an example. Environ. Pollut. 245, 965–974.
Wang, W., Zhou, C., Yang, Y., Zeng, G., Zhang, C., Zhou, Y., et al., 2021. Carbon nitride based photocatalysts for solar photocatalytic disinfection, can we go further? Chem. Eng. J. 404, 126540.
Yang, Y., Guo, Y., O'Brien, A.M., Lins, T.F., Rochman, C.M., Sinton, D., 2020. Biological responses to climate change and nanoplastics are altered in concert: full-factor screening reveals effects of multiple stressors on primary producers. Environ. Sci. Technol. 54 (4), 2401–2410.
Yoshikawa, T., Asoh, K., 2004. Entanglement of monofilament fishing lines and coral death. Biol. Conserv. 117 (5), 557–560.
Zettler, E.R., Mincer, T.J., Amaral-Zettler, L.A., 2013. Life in the “plastisphere”: microbial communities on plastic marine debris. Environ. Sci. Technol. 47 (13), 7137–7146.
Zhang, L., Zhang, S., Wang, Y., Yu, K., Li, R., 2019. The spatial distribution of microplastic in the sands of a coral reef island in the South China Sea: comparisons of the fringing reef and atoll. Sci. Total Environ. 688, 780–786.
Zhang, D., Liu, X., Huang, W., Li, J., Wang, C., Zhang, D., et al., 2020a. Microplastic pollution in deep-sea sediments and organisms of the Western Pacific Ocean. Environ. Pollut. 259, 113948.
Zhang, Y., Kang, S., Allen, S., Allen, D., Gao, T., Sillanpää, M., 2020b. Atmospheric microplastics: a review on current status and perspectives. Earth-Sci. Rev. 203, 103118.