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Review article

Effects of microplastic and heavy metals on coral reefs: A new window for analytical research

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ABSTRACT

In the modern world, plastic trash has been recognized as a global issue, and studies on microplastics (MPs) in the marine and inland environments have previously been conducted. Marine ecosystems act as a bio-diverse ecosystem where coral reefs contribute to make a sound living of the coastal people by gathering natural resources. The current study indicates that MPs and heavy metals (HMs) accumulation to biofilm and organic matter through sedimentation, precipitation, adsorption, and desorption that may have potential effect on growth and development of coral reefs in the marine ecosystems. However, the knowledge of distribution, impact, mechanism, degradation, and association mechanisms between MPs and HMs in the natural environment may open a new window for conducting analytical research from an ecological viewpoint. The current study thus summarizes the types of marine samples with the analytical techniques, polymers of MPs, and their impact on corals and other marine biota. This study also identifies existing knowledge gaps and recommends fresh lines of inquiry in light of recent developments in MPs and HMs research on the marine ecosystems. Overall, the present study suggests a sustainable intervention for reducing MPs and HMs from the marine ecosystems by demonstrating their existence in water, sediment, fish, corals, and other biota, and their impending ecotoxicological

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impacts on the environment and human health. The impacts of MPs and HMs on coral reefs are critically assessed in this study in light of the most recent scientific knowledge, existing laws, and new suggestions to minimize their contamination in the marine ecosystems.

1. Introduction

In the modern era, plastic is widely used in every aspect of our lives because of its affordability and diversity [1]. Now a day, it is very much popular to the civilized society because of their various sizes, shapes, colours, and extended lifespan. Fig. 1 represents the global production of plastics from 1950 to 2021 with the water bodies in the world through which plastic can transport to their final destination i.e., ocean. Plastic production abruptly increased during this time frame (1950–2021) where in 1950, the production stood 1.5 million metric tons and it was augmented to 390.7 million metric tons in 2021. At the end of their life cycle i.e., after utilization, this large quantities of plastics may undergo degradation through hydrolysis and other chemical weathering processes and finally they are fragmented into microplastic or nano plastics [2,3]. However, fragmented tiny plastic particles (size >5 mm) are commonly found in the natural environments are known as microplastics (MPs) [4]. Additional sizes for plastic pollution are also occurred in the marine environment such as mesoplastics: 1–5 mm, microplastics: 0.1 μm–1 mm, and nanoplastics: ≤0.1 μm [5,6]. Over time, fragmented plastic debris and micro beads (use in the industries and personal care products) can release various MPs polymers such as polyethylene (PE), polyvinyl chloride (PVC), and polypropylene (PP) and at the same time various toxic substances such as agrochemicals, incombustible, and potential toxic metals (PTMs) (e.g., Cr, As, Ni, Cu, Pb, and Cd). From inception, such chemicals might accumulate in the bottom of the aquatic water bodies up to a million times greater quantities than the estimated amounts in the natural environments [7–10]. However, MPs not only bring toxic substances but also give rise to pestilential and redox imbalance, destructive to

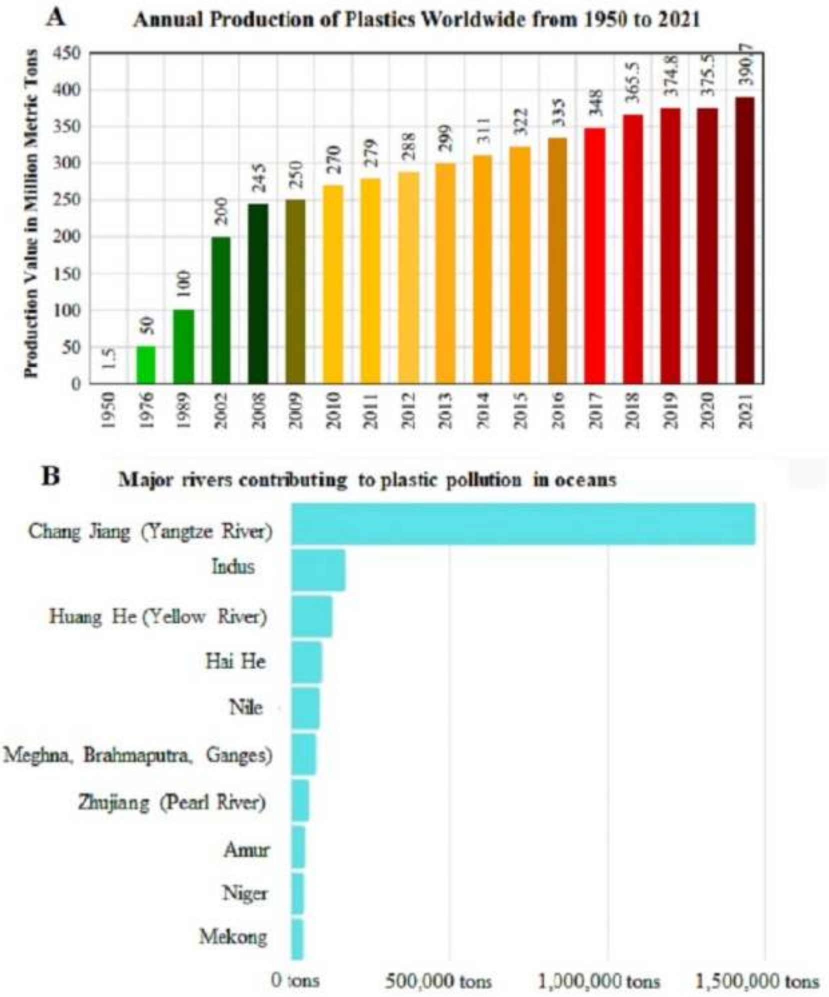

Fig. 1. Global plastics production (in million metric tons) from 1950 to 2021 (A) [16] and major MP Transporter rivers into the Ocean (B) [17].

the procreative organs, actinic response reticence, and progression impedance of the biota [11,12]. Therefore, microplastics can be noticed as an important carrier material for delivering various toxic chemicals including HMs to the marine organisms that create a significant concern to the world scientists in recent decades [13–15].

In the natural environment, both MPs and HMs can be regarded as the most harmful toxins [18], and their pollution in soil, sediment, water, coral reefs, and food is increasing due to rapid urbanization and industrialization [19–22]. Once they release to the environment, they can present for long time even 100 years or more [6,23]. As a result, their persistence, non-biodegradability, bio-accumulation, and toxicity to the biota in the both terrestrial and aquatic habitats are becoming of more importance to the research communities [24,25]. Both MPs and HMs tend to accumulate in the environmental matrices before creating adverse effects on human health via ingestion or inhalation (Fig. 2) [19,21,22,26]. For example, excess levels of As, Pb, and Cd may endanger fish cells, and constant contact with human tissue might lead to sickness or even death [27,28]. Owing to the bio-magnification of HM$_S$ in food systems and coral reefs, marine habitations are the best places to measure the severity of contamination of the marine ecosystems [29]. On the one hand, researchers, policymakers, and the public are paying close attention to manage MPs and HMs in a sustainable way; on the other hand, their pollution's still exist in the environment [30]. Therefore, assessment of MPs and HMs in the natural environment is very important for the survival of the living organisms in the aquatic ecosystems.

In the marine ecosystem, coral reefs play a vital role in sustaining a variety of marine creatures and they are maintaining balance in the natural habitations, diet bases, and livings [31]. Nevertheless, a number of challenges, such as contamination by MPs and HMs, overharvesting of fishes, and climate variability that reduce these sensitive and vulnerable habitats from the marine ecosystems [28,32]. The spatial variation, sources, and degradation of MPs and HMS in coral regions around the world are poorly understood, but what is known is that these tiny particles can build up in large concentrations in the water column and seabed surface sediments [17,33,34]. Considering the focus on pollution and coral bleaching by MPs and HMs, there is scant information about the presence and effects of small metallic and plastic elements on the coral reefs [35–37]. In recent times, investigators have been started their experiments to examine the intensity and ecotoxicological effects of MPs and HMs on the coral reefs [36,38]. In addition, a substantial lab scale experiments have been conducted to ascertain the underlying mechanisms of MPs and HMs that negatively affect the survival of corals in the marine environments [20,33,34]. However, the current review revealed the presence of MPs and HMs in the extra layer tissues of the coral's stomach cavity and identified the interaction mechanisms of heavy metals by MPs in the marine environment and their impacts on corals. The feeding and disconnected external bond strength of MPs and HMs are assumed to have a detrimental effect on the thermodynamic characteristics, growth and development, and nutrition of corals (Fig. 3). As a consequence, there is a reduction in feed consumption, photosynthetic efficiency, metabolic rates, and bone calcification [39–41]. The issue of elevated risks of MPs and HMs to coral reefs have garnered a significant attention in recent years, and understanding the frequency, causes, and dangers of these contaminants on coral reef settings became an essential issue.

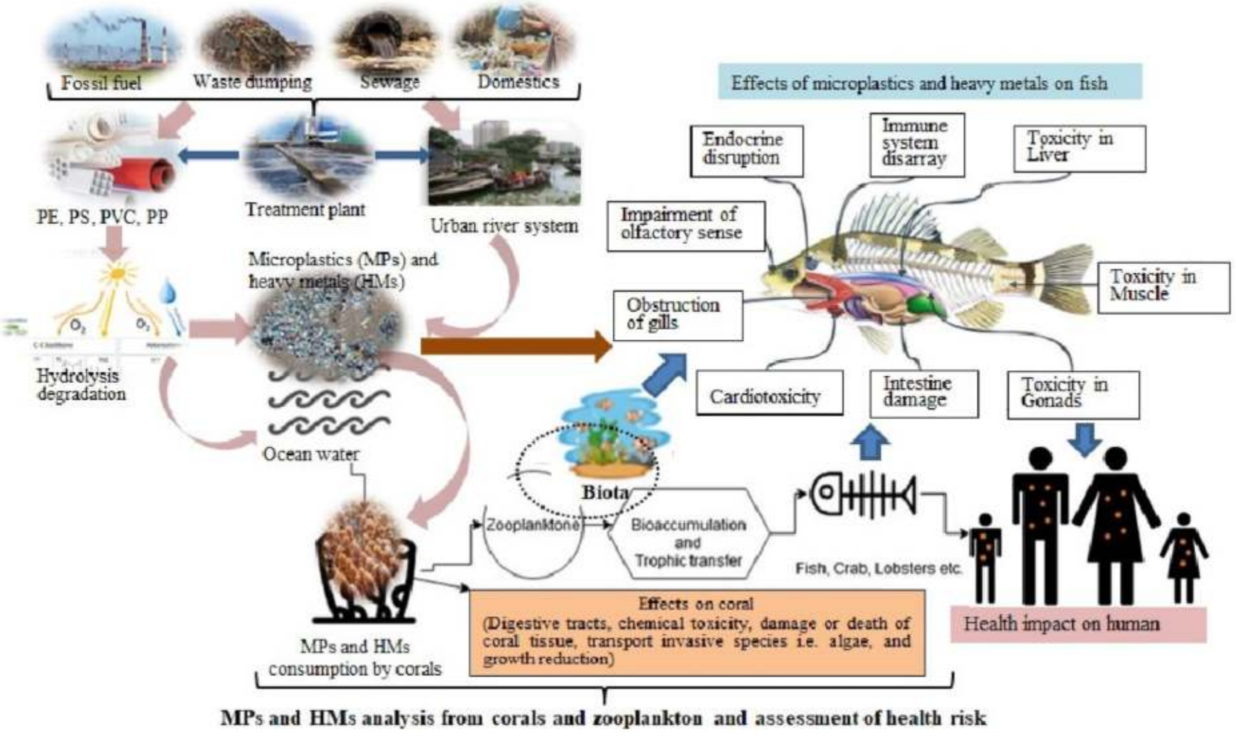

Fig. 2. Sources, degradation, and ecotoxicity mechanisms of microplastics (MPs) and heavy metals (HMs) on the corals and their impacts on the fish, biota and human health.

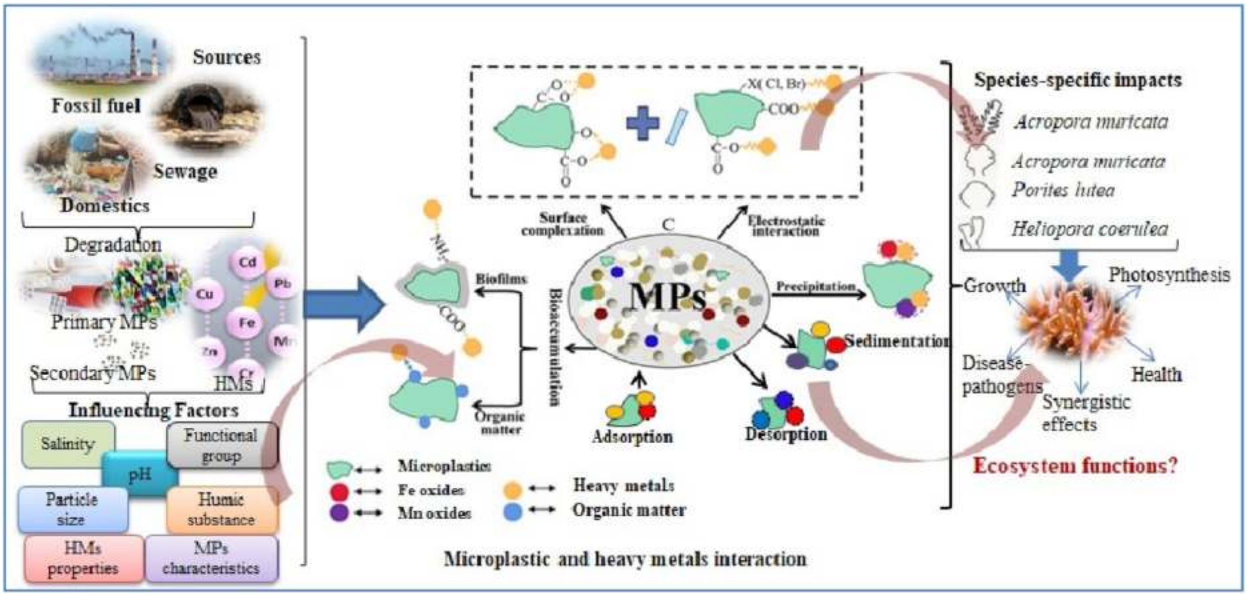

Fig. 3. Factors influencing the interaction behavior of heavy metals by MPs in the natural environment and their impacts on the coral. (Adjusted after modification from Cao et al. [42].

In the benthic ecosystems such as freshwater and saltwater, MPs and HMs presence, spatial traits, and their ecotoxicity impacts have undergone thorough studies over the last few years. However, no attempt has been made to characterize the fate, interaction mechanisms, and influences of MPs and HMs on coral reefs. Therefore, the current review aims are to assess the sources, degradation and impact of MPs and HMs on the coral reefs as well as human; to identify the mechanisms that connect MPs and HMs with coral reef ecosystems; to formulate policy for future evaluation to diminish MPs and HMs pollution on corals and to recognize existing gaps and forthcoming exploration essentials to open a new window for advanced analytical research.

2. Distribution and contamination of MPs in the marine ecosystems

A considerable amount of plastic wastes is entering into the ocean and is following the increasing trend. Table 1 provides a summary of some researches that focus on the sources of microplastics within coral reef ecosystems and polymer types in the global aquatic ecosystems. From the international research data bases, it has been observed that microplastics quantities in the coral biodiversity vary significantly among numerous regions in the world. Lechner et al. [43] reported around ~7.5 mg/m^3/s (1553 tons) of microplastics on a yearly average in the Black Sea. Wright and Kelly [44] predicted around 250 million tons of plastic leftover may have chance to deposit in the ocean by 2025. Varying concentrations of MPs has been observed at the ranges between 640 and 42,000 particles/km^2 in the North-western Pacific Ocean [45]. In eight metropolitan lakes in Changsha (China), a considerable quantity of microplastics was noticed which was varied from 2425 to 7050 items/m^3 [46]. In the Hong Lake's surface water, about 293–7924 particles/m^3 microplastics were also found [47] and Nakdong River, South Korea [47]. Abnormal levels of microplastics i.e., 1,72,000 to 4,19,000 items/m^3 were seen in the Saigon River's surface water in Vietnam [48]. The extraction procedure of microplastic is not familiar and easy for the researchers especially in developing countries. However, the assessment of microplastics in the ecological matrices such as surficial water and sediment, fish, corals, and other biota and is a stimulating commission that has been hindered by the lack of a widely established approach or the scarcity of data (Table 1).

The limitations of conventional surveillance and extraction approaches are the root cause of the information gaps for MP in the corals and other aquatic specimens are considerably worse. To overcome the extraction difficulties of MPs, now a day numerous other tactics have been used such as float and filtering for separate, FTIR, Raman spectroscopy for identification as well as quantification [20]. It is really crucial to design ultra - filtration membranes, as well as effective isolation methods include microwave disintegration, dew spot excavation, surface flowing partition, and pressurized liquid retrieval for complete extraction and separation of MPs without causing damage in the environmental media. Further practical exploration for MPs assessment in the corals habitats is urgently important or reduces their threat or toxicity [63]. The current study therefore highlighted some methodology for MPs extraction and assessment in the aquatic water body (Table 1).

Numerous MP types have been looked into the compartments of the marine environment such as water, sediment, fish, biota, and coral reefs which frequently incorporate a variety of dimensions, shapes, and exterior (Table 2). These microplastics are composed mostly of plastic polymers, including polypropylene (PP), polyethylene terephthalate (PET), polyamide (PA), polyvinyl chloride (PVC), polyethylene or polythene (PE), polystyrene (PS), polypropylene or polypropene (PU), PP-PE, polyformaldehyde (POM), and polyacrylonitrile (PAN). They are mostly derived by various activities in the marine environment such as fishing, shipping, domestic

Table 1
Microplastic contamination in worldwide marine and freshwater ecosystems.

Study location	Type of samples	Analytical procedure	Materials found	Polymer types found	Microplastic Source	References
North Yellow Sea, China	Surface water and sediment	Optical microscope equipped with an AxioCam digital camera	545 ± 282 items/m3 in water, 37.1 ± 42.7 items/kg in sediment	Polyethylene, polystyrene, and polypropylene	Fishing nets, ropes, and domestic sewage	[49]
Maldives in Magoodhoo Island (Indian Ocean)	Sea Water	In situ sampling; Micro FTIR analysis	8.9 particles/g of coral	Mostly PE, PP, and EPDM with PS, PL, PA and ACM	On site waste burning, waste management	[50]
South Korean Beach	Beach sediment	Fourier transform infrared spectroscopy.	1–5 mm MP: 0–2088 n/m^2; 0.02–1 mm MP: 1400–62,800 n/m^2	Expanded polystyrene and polyethylene	weathering and land based sources	[51]
East Asian seas around Japan	Surface water (75 cm)	Stereomicroscope, FTIR	3.74 ± 10.40 pieces/m3 (micro), 0.38 ± 1.06 pieces/m3 (meso)	polystyrene and polyethylene	Fragments of marine debris	[52]
Cabo Pulmo and Espiritu Santo Island, Baja California Sur, Mexico	Sand/ sediment	FTIR spectroscopic	Cabo Pulmo (avg. 680.25 items/100 g^{-1} dw) and from Espiritu Santo Island (avg. 321.75 items/100 g^{-1} dw)	PP, HDPE, LDPE, PS, PC, PU and RYN	Human-made and tourist-related actions governed by wave movement and tidal currents	[20]
Maldives in Maldivian archipelago (Indian Ocean)	Coral from 4 sites	Micro FTIR spectroscopy	1.0 ± 0.5 microplastics/ g	PS, PE, PVC, PC, PET and PP	Photo-oxidative degradation, biofouling and marine food chain with local sewage pipe in Thudufushi	[53]
Sanya Bay, China	Water and coral samples	Stereomicroscope analysis; micro-Raman spectrometer	Seawater ranging from 15.50 ± 1.50 items L−1, at DD to 22.14 ± 0.90 items L−1; A. millepora was 0.27 ± 0.26 items polyp 1 and G. fascicularis was 2.32 ± 0.86 items $polyp^{-1}$	PET,CP, and PE, PS, PA, PP and PP–PE	Extensive anthropogenic activities including rapid tourism development, sewage discharge and urbanization	[54]
Jepara coastal waters, Java Sea, Central Java, Indonesia	Sedimen	Fluorescent microscopy	Corals of Massive (9.75 ± 6.6), submassive (9.50 ± 3.3), folious (11.50 ± 4.5), and branching (17.75 ± 2.3 in kg-1	PS, PE	Fishing or by the discharge of textiles.	[38]
Gulf of Mannar (GoM),	Seawaters and sediment in 98 sampling site	ATR-FTIR (Thermo Nicolet model iS5)	28.4 to 126.6 items L^{-1} in water and 31.4 to 137.6 items kg^{-1} in sediment	PE, PP, PET, PA, AR, PEST, PS, PVC	Widespread waste management issues on the mainland shore	[36]
Xisha Islands, northwest part of South China Sea (SCS)	5 stations	Micro Fourier Transform Infrared Spectroscopy (μ-FT-IR, Spotlight 200i FT-IR microscopy system,	Bottom seawater (9.5 ± 3.7 particles L^{-1}), sediment (280.9 ± 231.9 particles kg^{-1}), Coral: P. damicornis (e 0.9 ± 0.5), G. fascicularis (1.2 ± 0.6) and P. lutea (2.5 ± 1.6) cm^{-2}	Moatly cellophane (61.13 %) and polyethylene, terephthalate (33.49 %)	Commercial and recreational fishing, shipping, tourism, and household sewage releases	[55]
Nansha Island, South China Sea(SCS)	Sea water (24 samples) and reef atolls(17)	Trawl sampling; extraction; FTIR spectroscopic mechanisms	Ranged from 0.0112 n/ m^3 to 0.149 n/m^3 with an avg. of 0.0556 ± 0.0355 items/m^3	PP and PE	Primary source are from fishing gear abrasions where nearby residential islands and high-intensity fishing activities are the local source	[33]
Vembar and Tuticorin Island, Indian Ocean	Sea water from 5 sites	Trawl sampling; extraction; FTIR spectroscopic mechanisms	60000-1,26,600 items/ m^3	PP, PE with PS, PA, PET, PVC, PEST, PEU, PVA and alkyd resin	Local water in the Ocean	[37]
Central Great Barrier Reef (GBR) World Heritage	Surface water(22), coral reef fish(60)	Sample collection from inshore and of shore reef; stereomicroscopic separation; microscopic	Marine microdebris on inshore (median = 4.5 fsh^{-1}, range 0–18 fsh^{-1}) and of shore (median =	Polyester (n = 86) > nylon(n = 79) > PE (n = 52)	Coastal river marine microdebris discharge	[56]

(continued on next page)

Table 1 (*continued*)

Study location	Type of samples	Analytical procedure	Materials found	Polymer types found	Microplastic Source	References
Area (WHA), Australia		photography; FTIR spectroscopy analysis	4.0 fsh^{-1}, range 0–131 fsh^{-1})			
Coral Reef Islands, South China Sea	Sand/ sediment	Renishaw micro-Raman spectrometer	90 ± 5, 530 ± 7 and 60 ± 3 to 610 ± 11 items/ kg	PP, PE, PET, PC, Nylon	Decomposition in lagoon sand, water exchange	[34]
Java and the Lesser Sunda Island, Indonesia	Sea water and fish in 3 sites	Trawl and visual sampling; extraction; microscopic inspection	Microplastic <5 mm was (≥78 %) where 0.04 to 0.90 pieces m-3 is from trawl survey and 210 to 40,844 pieces km^{-2} is from visual survey	PE and PET corresponds films and plastic bottles	Regional rivers and population density causes higher plastic abundance	[57]
Faafu atoll, Republic of Maldives, Indian ocean	Sea water in 12 sites	Trawl sampling; extraction; FTIR spectroscopic mechanisms	0.12 ± 0.09 items/m3 (0.03–0.65 items/m^3)	PE, PP, PA, PS, PU	Terrestrial sources are the primary contributors	[58]
Nansha Islands, South China Sea	Seawater	Microscopic inspection; RAMAN spectroscopy analysis	1733 items/m3	PVC > PA > PE > PP	Urban sewage, Ships or fishing activity	[59]
Fort Wetherill, Rhode Island, United states	4 Coral colonies	Micro FTIR spectroscopy	112 items/per polyp	PA > PS > PVC > fiber reinforced		[60]
Faafu atoll, Republic of Maldives, Indian ocean	12 sampling sites	Trawl and in situ sampling; extraction; Microscopic mechanism; FTIR spectroscopy analysis	0.32 ± 0.15 particles/ m^3 in the surface water and 22.8 ± 10.5 particles/m^2 in the beach sediments	PE,PP, PS	The burnt micro particles were frequently found close to the inhabited island.	[61]
Northeastern and Eastern shores, Hong Kong	Benthic sediment	Microscope Examination; Attenuated total reflectance—Fourier transform infrared spectroscopy (ATR-FTIR) analysis	189 ± 50 items/kg	Mostly polyethylene (PE; 51.9 %) and polyethylene terephthalate (PET; 29.3 %)	City itself and the Pearl River discharge	[62]

sewage, waste burning, land based sources, fragments of marine debris, wastewater, biofouling, waste from the marine food chain, tourism, photo-oxidative deterioration, and urban discharge (Table 1). MPs can be found in every marine area of the world which has drawn significant attention for investigating microplastic pollution to the critical location especially coral reef regions in the world [20,50,53,64]. Raguso et al. [50] obtained 8.9 particles/g of brown and pink colours MPs in some coral species such as *Porites lutea, Pavona varians,* and *Pocillopora verrucosa* in Faafu atoll, Maldives in Magoodhoo Island. Another research by Saliu et al. [53] observed 1.2 particles/g of MP (PS and PE polymers) in Haliclona (*Haplosclerida*) tissue in the Indian Ocean. Saliu et al. [58] found 0.12 ± 0.09 items/m^3 (0.03–0.65 items/m^3) MPs (PE, PP, PA, PS, and PU polymers) in *neuston* and *scleractinian* corals which was the main sources from terrestrial activities. Another study by Patti et al. [65] observed average amount of MPs of 277.90 ± 24.98 particles/kg in sediments at the central Indian Ocean.

Ding et al. [35] identified 7–4856 μm in diameter microplastic fragments in corals, fisheries specimens, and ocean samples from the South China Sea's Xisha Islands. Scientists determined MP with a detection limit of 1.0–44.0 items/individual on the surfaces of coral bones. Zhou et al. [55] examined the presence of microplastics in saltwater, coastal sediment, and three types of scleractinian corals (*Pocillopora damicornis, Galaxea fascicularis,* and *Porites lutea*) from the Xisha Islands, of the South China Sea. They also observed 9.5 ± 3.7 particles/L in seawater, 280.9 ± 231.9 particles/kg in sediment, and 0.9 ± 0.5, 1.2 ± 0.6 and 2.5 ± 1.6/cm^2 in coral samples of *P. damicornis*, *G. fascicularis,* and *P. lutea* which were 61.13 % for CP and 33.49 % for PET with green, blue, red, translucent, and black colours. These studies identified the profitable and leisure fishing, conveyance, and sightseeing industries are some of the producers of these microplastics in the marine setting. Overall the cradles of MP in the coastal area includes as the human discharge of waste through the river network, industrial effluents, fishing activity, and tourism or recreational activity [25,34,65,59].

3. Mechanism of MPs and HMs in coral and their impacts on fish, and human

Plastic is manufactured for a variety of uses. After utilization, plastic item can be discarded to the environment, and subsequently they are degraded to the microplastics [75]. Plastics are used extensively, which can be ascribed to produce different polymers of MPs through various processes [76]. Improper disposal of plastics signifies its presence in the marine ecosystems resulting the harm to corals, fish, and human [77]. The majority of these microplastics are produced during 2018–2021 and main contributors are China (Fig. 1 A, B). In the world, the main rivers that dump MPs into the ocean are the Indus and Yangtze rivers in China [17] (Fig. 1). Luo et al. [78] resolved that weathering effects on plastic polymers in the coastlines leads to micro-cracking for MPs disposal into the sea which can easily mix with the ocean water and consume by the corals (Fig. 2). As a result MPs can circulate throughout the cells of

Table 2
Types, concentration and shape of microplastics in the environment and their impact on the coral species.

Types of MPs	Size	Shape of MPs	Impacts on coral	References
PET	5–∼500 μm	fragments	MP particles have a species-specific influence on corals, with S. hystrix and M. capricornis incorporating particles more frequently.	[64]
PE	175.5 ± 73.5 μm	Rough surface structure	Decreased the rate of calcification and the skeletal development and nutrient cycling processes of coral skeletons.	[66]
PP,PS, PE	20–100 μm	fragments falling	Corals primarily consume polypropylene if exposure to MP, results in a variety of biological impacts ranging from eating loss to mucus formation and changed gene transcription.	[67]
Polyethylene	5–50 μm	fragments	Calcium homeostasis and tissue design optimization were adversely influenced including species' assessment groups after long outpouring. Exposure reduced floating mass in A. cervicornis.	[68]
PVC, PE, PET, and polyamide 66 (PA66)	1–10 μm	fragments	In 4 experimental sets, coral consumed MP, and MP exposure decreased the antioxidant ability, immune function, calcification, and calorie consumption of the coral Tubastrea aurea.	[69]
polyethylene (PE)	0–5 m	filaments	Potential impact of MP on Mediterranean stony coral species indicates ability to eat.	[70]
PP, PS, PC, PA, PVC, LDPE, PET, EPS, ABS	3–5 mm		Possible risk to coral vitality, and also to the overall biological stability of oceans as well as the safety of aquatic life.	[71]
LDPE MP, CAS 9002-88-4	1 μm–5 mm	Fiber > round particles > irregularly shaped particles	This research implies that MP can influence Z. sociatus photosynthetic rate, energy usage, antioxidants and detoxifying capabilities via absorption and/or surface adherence.	[72]
polyethylene (PE)	65 μm–410 μm	Irregularly, rough surface structure, resembling natural secondary microplastics	Energy needs in the afflicted species, most certainly as a result of direct interaction with the MP. According to the findings, microplastic contamination can harm hermatypic corals. Such impacts might make corals more vulnerable to other pressures, leading to ecological changes in coral ecosystems.	[40]
LDPE	<5 mm	Fibers	The decline in zooplankton consumption by Lophelia pertusa individuals partly coated by MP particles lowered the corals' food consumption, and hence likely limited the energy accessible for the creation of tri-dimensional habitation structures.	[73]
Microspheres; microbeads from face wash	3, 6, 11 μm; 3–60 μm		Ingestion of MP and Artemia nauplii containing MP greatly suppresses parasitic algal infection rate into the hosts; affects the establishment of parasitic partnerships	[74]

corals and cause cellular damage, inflammation, facultative detritivores, and growth suppression [79,66]. MPs can also bring HMs and viruses to coral reefs, which additional diminish feeding ability, and symbiotic relationship with other organisms [40,80]. Therefore, it is crucial to comprehend the linking mechanisms of MPs and HMs in the body of corals for successful mitigation strategies of MPs and HMs in the marine habitats.

In any of the marine environment, MPs and HMs might find their way into the food webs through the diet of corals by zooplankton and other biota, leading to their bioaccumulation and trophic transfer [81]. With the rise of MPs and HMs in the maritime setting, their consumption by fish, shellfish, or other biota also will be increased and may have negative effects on human health through food chain transfer [82,83]. Therefore, the current study was reviewed the hazardous effects of MPs and HMs on the important marine habitats i.e., corals and their subsequent transfer to human body via food chain. In Fig. 2, MPs and HMs originates from various sources and degrade to small particles and eventually accumulate in the body of corals. From the corals body, they may enter to the body of fish and human and create detrimental impact on human health. MPs and HMs have been seen to be consumed by marine animals including mussels, oysters, crabs, sea cucumbers, fish, and other biota [37] but lack of information regarding the shape, size, colours, and other chemical properties of MPs in foods [84]. Jiang et al. [46] mention that MPs act as a carrier material for different chemicals in the marine environment which have been related to fish endocrine disruption, modification of sex specific gene expression, cardiotoxicity, and intestine damage [47]. Concurrent consumption of MPs and HMs can alter the chromosome, causing cancer, obesity, and infertility [85,86]. Women's are exposed to MPs and HMs through the foods especially marine food items which has been associated with a higher chance in developing prostate cancer [87]. As cytotoxic activity and oxidative stress on human and animal health, MPs cause brain and epithelial cells to produce more reactive oxygen species, contributes to cytotoxicity [88]. Deng et al. [89] concluded that microbeads damage the system for metabolic enzymes activities that interrupt the energy balance in human body. However, a thorough analysis of the potential health concerns posed by MPs and HMs from the polluted marine food is necessary to control MPs and HMs pollution in the marine ecosystems.

4. Interaction between MPs and HMs and impact on the coral reefs

Table 2 summarize the characters of different MPs polymers and their impact on coral reefs globally. Since corals are fussy feeders, they eat small particles of MPs, and zooplankton from their surrounding environment. MPs consumption by corals leads to severe tissue defects such as species-specific influence on immunity system difficulties of *S. hystrix* and *M. capricornis* [64], decreased the rate of calcification and the skeletal development [66]; decreased anti-oxidant ability, resistant function, calcification, and calorie consumption of the coral species *Tubastrea aurea* [69]. During the transportation of MPs and HMs in the aquatic water bodies, they may transport pathogenic microbes and chemicals; therefore, they have harmful impact on coral ecosystems and endanger the coral ecology [90]. Fish, grubs, and other aquatic creatures are dependent on coral for their food that can produce toxins in the fish body through the process of biomagnification. The *P. verrucosa* is more susceptible to MPs contamination than other coral because of structural obstruction of its feeding processes [40]. The *Acropora* sp. was substantially more sensitive to MPs than *Seriatopora hystrix*, according to results of a related investigation [91]. Therefore, it is very important to explore the knowledge on the effect of MPs on the eating behaviour of coral reefs.

Though MPs and HMs are the toxic contaminants in the natural environment but their interaction was unknown to the scientists of the modern worlds. However, Ashton et al. [92] first reported the interface mechanisms between MPs and HMs in the water setting. Subsequently, several studies have using a range of heavy metals, including Co, Ni, As, Cr, Cu, Zn, Cd, Pb, and Hg [93–96]. Tang et al. [97,98] concluded that HMs adsorption on the virgin MPs is almost negligible if there is no change or modification of MPs, while the degraded MPs through the attachment of organic matter can make association with HMs [96] (Fig. 3). The original MPs turn to small fraction of MPs and make interaction with HMs through the process of sedimentation, adsorption, and desorption. In these processes, oxides of Fe and Al and organic matter help to make the association process between HMs and MPs (Fig. 3). The degraded MPs can bioaccumulate with the biofilm and organic matter that may help to make association between MPs and HMs. The associated products with biofilm or organic matter may help to open the new window for analytical research in the recent development of modern science. After breakdown to form new small products of MPs, the adsorption-desorption processes also help to make a new association between MPs and HMs though confirming continuous interactions between HMs, MPs, and sediments in the marine environment. In Fig. 3, the interaction modes of MPs and HMs are summarized that provides a quantitative understanding about the effects of various factors such as bioaccumulation (biofilm and organic matter), surface complexation, electrostatic interaction, precipitation, sedimentation, adsorption, and desorption on the connotation behavior of HMs with MPs that may affect the growth and development of the corals.

5. Knowledge gaps and unrevealed research theme

In the present world, limitation of research data and knowledge gap regarding MPs and HMs contamination in the typical

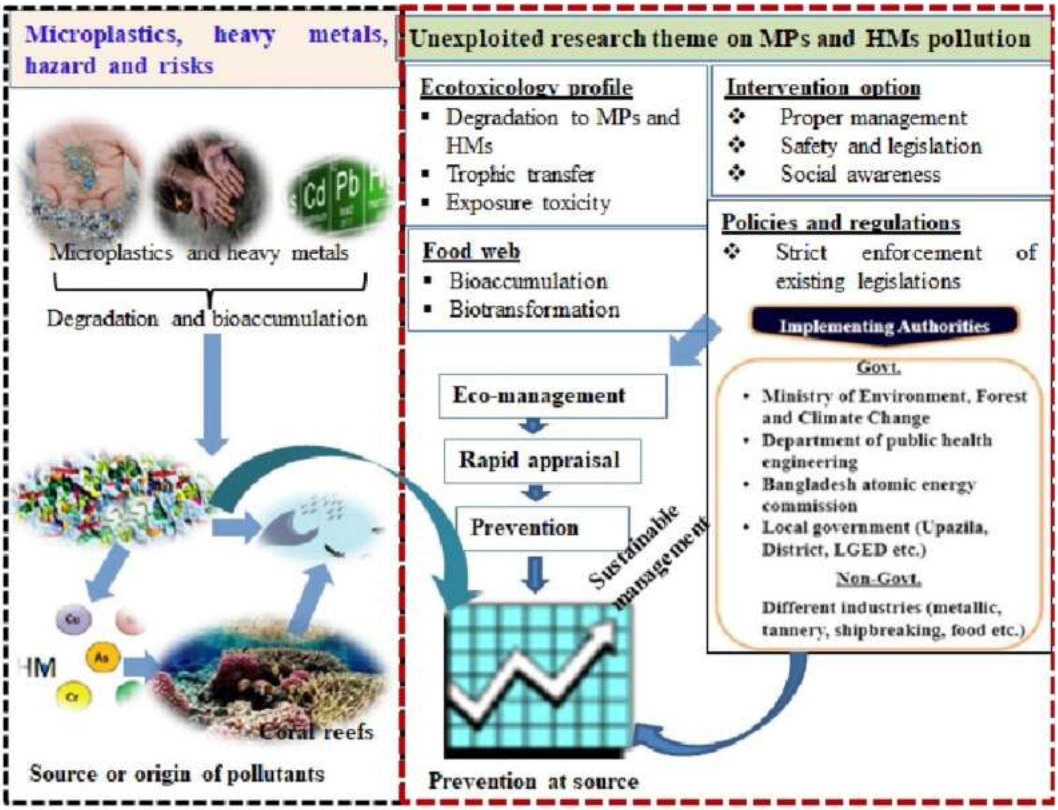

Fig. 4. Conceptual policy framework for sustainable management of microplastics (MPs) and heavy metals (HMs) pollution in the environment.

environment. Hence, it is quite difficult to evaluate the exact mechanisms of microplastics that are affecting corals and other aquatic biota globally. A considerable knowledge gaps on the production of MPs polymers, their degradation to marine environment, and public health. The main contributors of HMs and MPs pollution are the developing country, though most of the developing country presently acknowledged for the international significance of plastic pollution and disaster cause by MPs. Studies on the pollution caused by plastic and MPs in the aquatic environment are now being carried out but the effect of MPs and HMs on corals and the interaction mechanisms between HMs and MPs are not studied yet.

Recent study by Calero et al. [98] discussed the removal of MPs and HMs from discharged water using advanced treatment techniques before it reaches outside sources. Absorption and flocculation are two important techniques can be used for mitigation of MPs in the aquatic ecosystems [99]. After degradation, MPs produce hydrophobic nature synthetic fibers that are not easily biodegradable, such as polyester and polypropylene, outstanding in the compartment of the environment (water, soil, sediment, and biota) for long times, and may significantly affect human wellness such as headache, skin irritation, breast cancer, neurotoxicity, genotoxicity, lung disease etc., through trophic transfer [100] (Fig. 4). From this extensive review, the current study has been explored some important issues on MPs and HMs degradation in the marine environment, but some unexploited research themes need to be explored such as the mechanisms of MPs and HMs interaction, trophic transfer, exposure toxicity, bioaccumulation, and biotransformation. This is the important findings for this review to find the future direction of research on the interaction mechanisms of MPS and HMS on the coral reefs in any of the marine environment on the globe.

Though some investigations on the MPs and HMs effluence have already been conducted in the aquatic environment but a lot of unexploded research themes need to be explored, such as ecotoxicity of MPs and HMs with their degradation and trophic transfer, bioaccumulation to food chain, and their biotransformation. As an intervention option for their sustainable management, safety and legislation, and the social awareness should be increased. For policy implication, different regulatory tools and procedures can be used to achieve environmental policy, which aims to mitigate the present MPs and HMs effluence in the maritime ecologies and to progress the current state of the environment [101] (Fig. 4). Alpizar et al. [102] suggested a useful method for tracking the flow of social and ecological measuring data in relation to MPs, intended to cut down on ocean plastic pollution. Creating social awareness almost prevailing situation about the MPs and HMs pollution and proposed regulations and the reduction of single-use plastics usage. Thus, the current study is recommending a co-management paradigm to prevent the illegal dumping of refractory plastic waste and dangerous compounds containing micro-beads into the marine ecosystems. The discussion from the current study on MPs and HMs management to save the coral reefs an important marine habitat can be accomplished by enhancing connection among the government, non-government organizations, scientists, and executing the policies and regulation, as illustrated in Fig. 4.

6. Conclusion and recommendation for future study direction

The current review emphasized microplastics and heavy metals pollution, their degradation, and interaction mechanisms for creating negative impacts on the coral reefs. The present study also summarizes the typical sources of microplastics and HMs in the marine coral ecosystems such as commercial fishing, wastewater discharge, atmospheric deposition, population density, and mismanagement of waste in the marine ecosystems. Recent studies have identified the presence of microplastics and heavy metals in the compartments of marine environment such as water, sand, coral, sediment, fish, and other aquatic habitats [33,36,37,55,103,104]. Considering the study of MPs on coral reefs, dissimilar investigations admitted numerous gaps comprising incidence of MPs on wild corals [53], mechanisms of MPs on coral tissue for reducing their growth and nutrient uptake [53,55], negative effect of MPs on the physiology of corals [105] whereas other research emphasized the distribution, quantity, characteristics, and consequences of MPs on corals (Tables 1 and 2).

The present study also explored the interaction mechanisms of MPs and HMs in the natural environment such as bioaccumulation (biofilm and organic matter), surface complexation, electrostatic interaction, precipitation, sedimentation, and adsorption and desorption. The important finding of the current reviews identified the post effect interaction of MPs and HMs on the corals especially cell browning, skeleton, molecular stress, and death. The current study suggested future study direction in revealing the impact of HMs and MPs on corals and other aquatic habitats based on ecotoxicological, movement of water and sediment, exposure, ecomanagement, and intervention with policies and regulation. Further research is recommended to understand the routes of detrimental and favorable consequences of microplastics and heavy metals particles on corals, fish, and other aquatic biota including molecular mechanisms and the repercussions of plastically bacteria or chemicals under the scenarios of climate change. The creation of efficient coral reef protection methods and the reduction of microplastic and heavy metals environmental emissions are critical. Also, the current study emphasized the further research to understand the health risks posed by microplastics and heavy metals to coral reefs, especially in relation to their interaction mechanisms and impact on human wellbeing. To establish the possible hazards of ingesting tainted aquatic food to public health, a thorough investigation and study of the potential health concerns from microplastics and heavy metals detected in diverse food products across the complete diet is also required.

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All authors have read, understood, and have complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors and are aware that with minor exceptions, no changes can be made to authorship once the paper is submitted.

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Md Saiful Islam: Writing – original draft, Project administration, Investigation, Data curation. **Abu Reza Md Towfiqul Islam:** Writing – review & editing, Investigation, Conceptualization. **Zulhilmi Ismail:** Writing – review & editing, Project administration, Conceptualization. **Md Kawser Ahmed:** Writing – review & editing, Visualization, Investigation, Conceptualization. **Mir Mohammad Ali:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Md Humayun Kabir:** Writing – review & editing, Validation, Conceptualization. **Khalid A. Ibrahim:** Visualization, Funding acquisition, Conceptualization. **Rahmah N. Al-Qthanin:** Validation, Supervision, Funding acquisition, Conceptualization. **Abubakr M. Idris:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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