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Short communication

Macro- and microplastics as complex threats to coral reef ecosystems

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ABSTRACT

The impacts of macroplastics (macro-), microplastics (MPs, <5mm), and nanoplastics (NPs, <100 nm) on corals and their complex reef ecosystems are receiving increased attention and visibility. MPs represent a major, contemporary, sustainability challenge with known and unknown effects on the ocean, and coral reef ecosystems worldwide. However, the fate and transport processes of macro-, MPs, and NPs and their direct and indirect impacts on coral reef ecosystems remains poorly understood. In this study, we verify and briefly summarize MPs distribution and pollution patterns in coral reefs from various geographical regions and discuss potential risks. The main interaction mechanisms show that MPs may substantially affect coral feeding performance, proper skeletal formation, and overall nutrition and, thus, there is an urgent need to address this rapidly growing environmental problem. From a management perspective, macro-, MPs, and NPs should, ideally, all be included in environmental monitoring frameworks, as possible, to aid in identifying those geographical areas that are most heavily impacted and to support future prioritization of conservation efforts. The potential solutions to the macro-, MP, and NP pollution problem include raising public awareness of plastic pollution, developing robust, environmental, conservation efforts, promoting a circular economy, and propelling industry-supported technological innovations to reduce plastic use and consumption. Global actions to curb plastic inputs, and releases of macro-, MP, and NP particles, and their associated chemicals, to the environment are desperately needed to secure the overall health of coral reef ecosystems and their inhabitants. Global scale horizon scans, gap analyses, and other future actions are necessary to gain and increase momentum to properly address this massive environmental problem and are in good accordance with several relevant UN sustainable development goals to sustain planetary health.

1. Introduction

Coral reef ecosystems are three-dimensional, complex, benthic structures distributed globally and provide human nutrition, habitat, food, resources, and breeding areas for a diverse array of inhabitants including marine fish (Hall et al., 2015). Coral reefs cover approximately 250,000 km^2 of the ocean and harbor an impressive reserve of marine biodiversity (25%), especially considering their overall size and global area proportion (1%). These complex ecosystems have important economic, ecological, and cultural values and coral reefs are economically important for >500 million people worldwide, and are critical habitats within the context of biodiversity (Wild et al., 2011), and global climate change mitigation (Huang et al., 2021, Spalding and Brown 2015).

Plastic products are widely used throughout society due to their low cost, physical–chemical properties, and durability. Over the past 60 years, the development of industrialized societies and human population growth have collectively led to a substantial increase in plastic use (Du and Wang 2021, Geyer et al., 2017). In tandem, plastic pollution has increased exponentially, posing a considerable threat to marine ecosystems such as coral reefs (Lavers and Bond, 2017). Scientists have estimated that approximately 11.1 billion plastic particles are found in the environment with a predicted increase of 40% by 2025 across the Asia-Pacific ocean basin alone (Lamb et al., 2018). Successful management of macroplastics (macro-), microplastics (MPs), and nanoplastics

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(NPs), and their associated chemicals is therefore vital to protect ecosystem health (Bank and Hansson 2019, Bank et al., 2022, Bank et al., 2020), and highlights the need for robust and targeted conservation efforts.

Coral reefs are complex ecosystems that are vulnerable to anthropogenic activities and environmental stressors, including marine pollution, light depravation, ocean acidification, deoxygenation, rising sea temperatures, rapid climate change, and pathogen-induced diseases (Hughes et al., 2018). Corals are considered ecosystem engineers (Wild et al., 2011) and from an evolutionary standpoint, macro-, MPs and NPs are relatively new threats to coral reefs (Huang et al., 2021, Pantos 2022, Reichert et al., 2022). Moreover, owing to the complex interactions between corals and plastic particles of different sizes, macro-, MPs and NPs may negatively impact corals differently, via entanglement, feeding, and covering/asphyxiation (de Carvalho-Souza et al., 2018) and responses to MPs have been reported to be species-specific (Mouchi et al., 2019). Plastic particles of different size classes enter these ecosystems, and have been shown to increase the risk of coral disease in the Asia-Pacific region (Lamb et al., 2018). Owing to the long lifespan, slow degradation, and potential long-term toxicity (Rillig et al., 2021), plastic-related damage and impacts to corals will likely persist for decades even if plastic production and waste streams are abruptly stopped.

The specific objectives of this investigation were to briefly summarize the threats and impacts of macro-, MPs, and NPs on coral reef ecosystems. We also discuss potential mitigation strategies for macro-, MPs, and NPs, and suggest approaches to identify geographical areas where MP pollution should be prioritized.

2. Discussion

Macroplastics gradually decompose into secondary MPs and NPs primarily as a result of degradation from weathering, mechanical wear, UV photodegradation, hydrolysis, biological ingestion, and biodegradation (Dawson et al., 2018). MPs are ingested by corals and may cause oxidative DNA damage and alteration of expression levels of key genes including *MnSOD*, which serves as the first defense against reactive oxygen species (ROS) (Corinaldesi et al., 2021). Conversely, Zhou et al. (2023) reported that corals employ heterotrophic plasticity to cope and maintain lipid reserves and can be remarkably tolerant to microplastic pollution. Collectively, these findings have led to questions about their potential toxicity to corals under environmentally relevant conditions.

MPs may become attached on the skeleton surface of corals and a 74.1% detection rate of MPs has been observed on the inside of skeletons (Ding et al., 2019). Although MPs in corals have been investigated there are limited data on effects of MPs on ecosystem structure and function, and trophic transfer dynamics in coral reef ecosystems. Therefore, a more comprehensive understanding of the distribution, fate, and potential risks associated with macro-, MPs and NPs is urgently needed (Fig. 1).

MPs are ubiquitous and found across a wide array of marine habitats (i.e., epipelagic, pelagic, mesopelagic and hadal zones, and throughout deep-sea, benthic ecosystems) and within coral reef ecosystems in the Pacific Ocean, Southeast Asia, the Indian Ocean (Patti et al., 2020), South China Sea (Ding et al., 2019), and the Atlantic Ocean (Macieira et al., 2021). MPs have also been observed in coastal areas (Liu et al., 2021), on beaches (Lo et al., 2018), in deep-sea habitats (Eo et al., 2021), mangroves (John et al., 2022), submarine canyons (Angiolillo et al., 2021, Tubau et al., 2015), and within polar regions (Mishra et al., 2021). MPs pollution is serious and extreme, and extends from shallow areas to deep marine trenches, even contaminating some of the earth's most remote areas (Napper et al., 2020, Raguso et al., 2022). For example, MP concentrations in surface waters ranged from 60,000 to 126,600 items/m^3 for the most abundant fibers (1–3 mm) (Patterson et al., 2020). MPs concentrations ranged from 1400 to 8100 items/m^3 (>80% were <0.5 mm) at Zhubi Reef, ranged from 1250 to 3200 items/m^3 at Nanxun Reef, and from 0.148 to 0.842 items/m^3 in the Nansha Islands (Huang et al., 2019, Nie et al., 2019, Wang et al., 2019). In another study, the MP concentration ranged 0.0112–0.149 items/m^3 (>70% of the fibers were <3 mm) in remote, uninhabited, reef atolls from Nansha Islands (Tan et al., 2020). Collectively, these data suggest that micro-, MPs, and NPs pollution of coral reef ecosystems is extremely widespread, but likely not uniform regarding overall risk, impacts, and overlap with areas of high degrees of biodiversity.

Recently, scientists determined that MPs affect corals both directly and indirectly, and that both active uptake and passive surface adhesion occur (Martin et al., 2019). The most direct impact is through ingestion (Chapron et al., 2018, Reichert et al., 2018), whereas indirect impacts occur via the substrate and are produced by colonization by invasive organisms on plastic surfaces (Barnes 2002), as well as from environmental plastic leachates (Li et al., 2016). Corals ingest MPs through attachment to tentacles and mesenterial filaments (Allen et al., 2017,

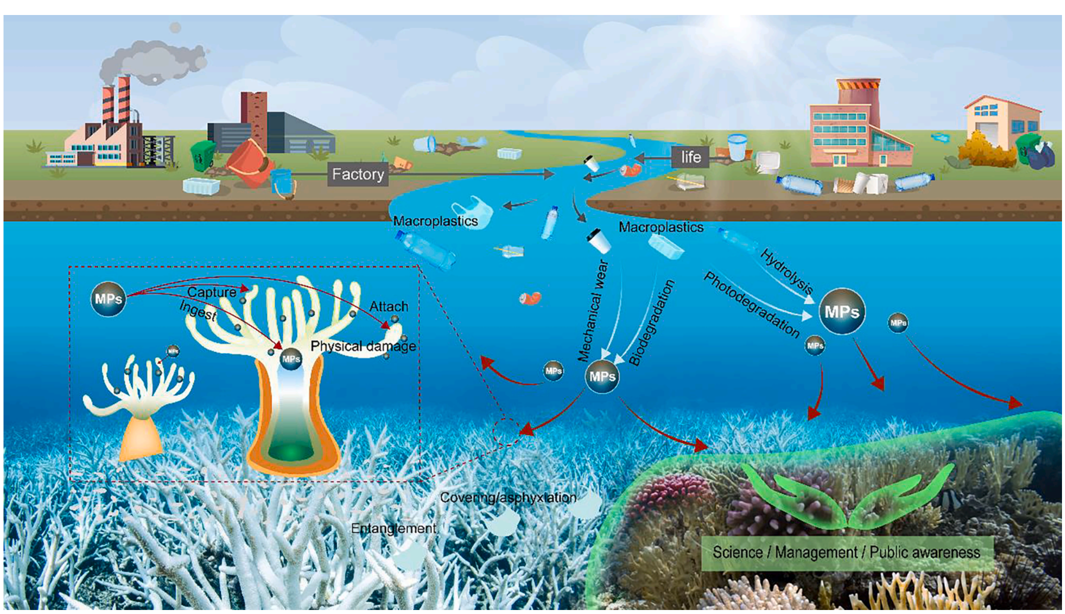

Fig. 1. Distribution, fate, and potential hazards associated with macroplastics (macro-) and microplastics (MPs) to corals and their ecosystems.

Reichert et al., 2018). MP particles may also be embedded in the tissues of temperate *Astrangia poculata* (Rotjan et al., 2019) and in the skeletons of tropical coral species (Krishnakumar et al., 2021). Moreover, the extent to which MPs attach to coral structures may be modulated by feeding behavior, ocean circulation patterns, wind, and morphology of coral species (Chapron et al., 2018, Martin et al., 2019).

Macro-, MPs, and NPs may have negative impacts on coral health (Hall et al., 2015, Huang et al., 2021, Pantos 2022). Coral exposure to plastics and MPs can adversely affect energy dynamics, physiology, growth, and population performance. MPs may inhibit coral predation (Hankins et al., 2021), act as carriers of coral albinism pathogens (Feng et al., 2020), and likely alter species-specific feeding strategies (Joppien et al., 2022, Savinelli et al., 2020). MPs inhibit nutrient uptake, photosynthesis, and detoxification often leading to oxidative stress, apoptosis, and growth inhibition. These effects are similar to the negative impacts of MPs observed on *C. goreaui*–Symbiodiniaceae symbiosis (Su et al., 2020). Moreover, zooxanthellae symbiosis, bleaching, and tissue necrosis have also been reported (Okubo et al., 2018). However, the exact mechanism by which MPs cause adverse reactions in corals remains poorly understood. It is possible that ingestion of MPs may block the digestive tract of corals, preventing proper food digestion. Most concerningly, corals are stationary organisms and voluntarily ingest MPs because they are attracted to their taste, possibly because of the chemical additives (chemical reception mechanisms). MPs may attach to coral tissue and can reduce prey capture capabilities causing energy loss owing to the need for MP removal from their surfaces.Plastic debris also causes physical damage to coral tissues, leading to adverse reactions by promoting pathogen invasion or depleting resources for immune system function during organism recovery.

NPs are defined as <100 nm and are of considerable toxicological concern (Hartmann et al., 2019). The knowledge gaps for NPs are far greater than for macro- and MPs owing to the restrictions and lack of robust NP analytical chemistry techniques and exposure sampling in coral reefs. Although a variety of techniques have been applied to the separation, identification, and quantification of MPs in various environmental substrates (Hernandez et al., 2022), most techniques, such as filtration, flotation, and Raman spectroscopy, are not suitable for detecting NPs due to their nanoscopic size. Harmonized, effective and advanced analytical techniques would improve the sensitivity and resolution of NP assays and more research in this area is desperately needed (Li et al., 2020). Further development of spectroscopic techniques, advanced mass spectrometry, and other thermal analysis will contribute to the nondestructive identification of NPs. Therefore, the negative influences of NPs are a high priority since these particles likely have important chemical and physical hazards for corals due to their small size (Li et al., 2020, Huang et al., 2021).

Increasing ocean temperatures and MPs negatively affect coral reef ecosystems. Climate-related disease outbreaks are already affecting coral reefs worldwide, and impact frequency and severity will likely continue to increase as ocean temperatures rise (Maynard et al., 2015). MPs transport pathogens within and among coral reefs promoting their spread and increase in the risk of infections. Plastic-contaminated reefs may be 22 times more at risk than highly preserved reefs, with the risk of disease increasing from 4% to 89% (Lamb et al., 2018). Plastic waste in the ocean makes reef-building corals highly susceptible to potentially fatal diseases (Kirstein et al., 2016). The secondary or indirect effects of MPs are likely the most important, especially when considered within the context of climate change, associated chemicals, increased ocean temperatures, and pathogens (Bank et al., 2020). However, the fate and transport processes and overall impacts of MPs and NPs in coral reefs remain poorly understood and require further attention and research.

MPs and NPs may affect coral population health, and the solutions to the plastic pollution problem are undoubtedly highly complex (Bank et al., 2022). Concerted efforts are needed to alleviate the current regional and global pressures of MPs on coral reefs to avoid potential ecosystem collapse. From a management perspective, macro-, MPs, and NPs should all be included as part of environmental monitoring frameworks and specifically for long-term global plastic observation systems (Bank et al., 2021) that could be established to evaluate particle size-specific mass balances, and status in coral reefs. Future research and development should focus on radically reducing MP contamination, improving waste management, reducing plastic consumption, developing circular economies, and eliminating MP inputs into the ocean. Strong remediation and conservation measures at international and national levels are urgently needed to address this problem. Improving wastewater management infrastructure is also critical in developing countries, and although this infrastructure is being improved, industrialized countries can immediately begin to curb the production and use of single-use plastics. Plastic waste management is, therefore, foundational to reducing the complex array of threats to coral reef ecosystems and potentially to human health.

Anthropogenic activities continuously contribute to macro-, MPs, and NPs pollution, creating environmental challenges that requires ongoing research. First, it is essential to understand the extent to which macro-, MPs, and NPs affect corals and their reef ecosystems. Secondly, the influences of MPs and NPs on coral's potential mechanisms and health require intensive studies using realistic environmental conditions (Zimmermann et al., 2021). Thirdly, exploring the potential synergistic effects of macro-, MPs and NPs with climate and global environmental change factors (Bank et al., 2022) on corals is urgently needed. Such investigations could be linked to field and laboratory-based research on the hazardous effects of plastic of different size fractions on coral reefs especially given the long-term, expected, and increased toxicity caused by NPs, surface chemistry, and *in vivo* accessibility (Huang et al., 2021).

Raising public awareness on plastic pollution and environmental protection issues may also stimulate industry-supported, technological innovations to reduce plastic use and consumption. The most effective mitigation strategy is to reduce plastic input into the ocean; however, global plastic recycling and international waste and trade dynamics must also be considered (Bank et al., 2021). Therefore, immediate global action to curb future plastic inputs is vital to securing the future health of coral reefs. Most strikingly, rather than debate whether plastic pollution or climate change is a greater threat, a more productive discourse would be to recognize that they are fundamentally linked and consider a systems-level approach to tackle both issues concomitantly (Bank et al., 2022).

3. Conclusions

Coral reef ecosystems face a wide array of interacting threats, including macro-, MP, and NP pollution. Corals are considered ecosystem engineers since they provide resources and habitat for a diverse array of deep-sea species. Macro-, MPs, and NPs may have negative impacts on coral feeding behavior and prey capture, skeletal growth and formation, and overall nutrition. Macro-, MPs, and NPs, and their associated chemicals, represent complex, chemical, and physical threats to both corals themselves, and to the diverse array of marine species and resources that inhabit these ecosystems. Future research and management should focus on developing global prioritization schemes and horizon scans to identify those areas where conservation efforts are most needed in the collective context of geography, biodiversity hotspots, feasibility, and human nutrition and societal needs.

CRediT authorship contribution statement

Wei Zhang: Conceptualization, Writing – original draft, Visualization. **Yong Sik Ok:** Writing – review & editing. **Michael S. Bank:** Writing – review & editing. **Christian Sonne:** Writing – review & editing.

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

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References

Allen, A.S., Seymour, A.C., Rittschof, D., 2017. Chemoreception drives plastic consumption in a hard coral. Mar. Pollut. Bull. 124 (1), 198–205.
Angiolillo, M., Gerigny, O., Valente, T., Fabri, M.C., Tambute, E., Rouanet, E., Claro, F., Tunesi, L., Vissio, A., Daniel, B., Galgani, F., 2021. Distribution of seafloor litter and its interaction with benthic organisms in deep waters of the Ligurian Sea (*Northwestern Mediterranean*). Sci. Total Environ. 788, 147745.
Bank, M.S., Hansson, S.V., 2019. The plastic cycle: a novel and holistic paradigm for the Anthropocene. Environ. Sci. Tech. 53 (13), 7177–7179.
Bank, M.S., Ok, Y.S., Swarzenski, P.W., 2020. Microplastic's role in antibiotic resistance. Science 369 (6509), 1315.
Bank, M.S., Swarzenski, P.W., Duarte, C.M., Rillig, M.C., Koelmans, A.A., Metian, M., Wright, S., Provencher, J.F., Sanden, M., Jordaan, A., Wagner, M., Thiel, M., Ok, Y. S., 2021. Global plastic pollution observation system to aid policy. Environ. Sci. Tech. 55 (12), 7770–7775.
Bank, M.S., Mitrano, D.M., Rillig, M.C., Lin, C.S.K., Ok, Y.S., 2022. Embrace complexity to understand microplastic pollution. Nat. Rev. Earth Environ. 3 (11), 736–737.
Barnes, D.K.A., 2002. Biodiversity-invasions by marine life on plastic debris. Nature 416 (6883), 808–809.
Chapron, L., Peru, E., Engler, A., Ghiglione, J.F., Meistertzheim, A.L., Pruski, A.M., Purser, A., Vetion, G., Galand, P.E., Lartaud, F., 2018. Macro- and microplastics affect cold-water corals growth, feeding and behaviour. Sci. Rep. 17, 15299.
Corinaldesi, C., Canensi, S., Dell'Anno, A., Tangherlini, M., Di Capua, I., Varrella, S., Willis, T.J., Cerrano, C., Danovaro, R., 2021. Multiple impacts of microplastics can threaten marine habitat-forming species. Commun. Biol. 4 (1), 431.
Dawson, A.L., Kawaguchi, S., King, C.K., Townsend, K.A., King, R., Huston, W.M., Nash, S.M.B., 2018. Turning microplastics into nanoplastics through digestive fragmentation by Antarctic krill. Nat. Commun. 9, 1001.
de Carvalho-Souza, G.F., Llope, M., Tinoco, 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.
Ding, J.F., Jiang, F.H., Li, J.X., Wang, Z.X., Sun, C.J., Wang, Z.Y., Fu, L., Ding, N.X., He, C.F., 2019. Microplastics in the coral reef systems from Xisha Islands of South China Sea. Environ. Sci. Tech. 53 (14), 8036–8046.
Du, H., Wang, J., 2021. Characterization and environmental impacts of microplastics. Gondw. Res. 98, 63–75.
Eo, S., Hong, S.H., Song, Y.K., Han, G.M., Seo, S., Shim, W.J., 2021. Prevalence of small high-density microplastics in the continental shelf and deep sea waters of East Asia. Water Res. 200, 117238.
Feng, L.M., He, L., Jiang, S.Q., Chen, J.J., Zhou, C.X., Qian, Z.J., Hong, P.Z., Sun, S.L., Li, C.Y., 2020. Investigating the composition and distribution of microplastics surface biofilms in coral areas. Chemosphere 252, 126565.
Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3 (7), e1700782.
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., Moso, E., Lasseigne, D., 2021. Microplastics impair growth in two atlantic scleractinian coral species, *Pseudodiploria clivosa* and *Acropora cervicornis*. Environ. Pollut. 275, 116649.
Hartmann, N.B., Huffer, T., Thompson, R.C., Hassellov, M., Verschoor, A., Daugaard, A. E., Rist, S., Karlsson, T., Brennholt, N., Cole, M., Herrling, M.P., Hess, M.C., Ivleva, N. P., Lusher, A.L., Wagner, M., 2019. Are we speaking the same language? Recommendations for a definition and Categorization framework for plastic debris. Environ. Sci. Tech. 53 (3), 1039–1047.
Hernandez, I., Davies, J.S., Huvenne, V.A.I., Dissanayake, A., 2022. Marine litter in submarine canyons: a systematic review and critical synthesis. Front. Mar. Sci. 9, 965612.
Huang, W., Chen, M., Song, B., Deng, J.Q., Shen, M.C., Chen, Q., Zeng, G.M., Liang, J., 2021. Microplastics in the coral reefs and their potential impacts on corals: a mini-review. Sci. Total Environ. 762, 143112.
Huang, Y.J., Yan, M.T., Xu, K.H., Nie, H.Y., 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., Heron, S. F., Hoey, A.S., Hoogenboom, M.O., Liu, G., McWilliam, M.J., Pears, R.J., Pratchett, M.S., Skirving, W.J., Stella, J.S., Torda, G., 2018. Global warming transforms coral reef assemblages. Nature 556 (7702), 492–496.
John, J., Nandhini, A.R., Chellam, P.V., Sillanpaa, M., 2022. Microplastics in mangroves and coral reef ecosystems: a review. Environ. Chem. Lett. 20 (1), 397–416.
Joppien, M., Westphal, H., Stuhr, M., Doo, S.S., 2022. Microplastics alter feeding strategies of a coral reef organism. Limnol. Oceanogr. Lett. 7 (2), 131–139.
Kirstein, I.V., Kirmizi, S., Wichels, A., Garin-Fernandez, A., Erler, R., Loder, M., Gerdts, G., 2016. Dangerous hitchhikers? Evidence for potentially pathogenic *Vibrio* spp. on microplastic particles. Mar. Environ. Res. 120, 1–8.
Krishnakumar, S., Anbalagan, S., Hussain, S.M., Bharani, R., Godson, P.S., Srinivasalu, S., 2021. Coral annual growth band impregnated microplastics (*Porites* sp.): a first investigation report. Wetl. Ecol. Manag. 29 (5), 677–687.
Lamb, J.B., Willis, B.L., Fiorenza, E.A., Couch, C.S., Howard, R., Rader, D.N., True, J.D., Kelly, L.A., Ahmad, A., Jompa, J., Harvell, C.D., 2018. Plastic waste associated with disease on coral reefs. Science 359 (6374), 460–462.
Lavers, J.L., Bond, A.L., 2017. Exceptional and rapid accumulation of anthropogenic debris on one of the world's most remote and pristine islands. P. Natl. A. Sci. 114 (23), 6052–6055.
Li, H.X., Getzinger, G.J., Ferguson, P.L., Orihuela, B., Zhu, M., Rittschof, D., 2016. Effects of toxic leachate from commercial plastics on larval survival and settlement of the barnacle *Amphibalanus amphitrite*. Environ. Sci. Tech. 50 (2), 924–931.
Li, P., Li, Q.C., Hao, Z.N., Yu, S.J., Liu, J.F., 2020. Analytical methods and environmental processes of nanoplastics. J. Environ. Sci. 94, 88–99.
Liu, K., Zhang, Z.W., Wu, H., Wang, J.X., Wang, R., Zhang, T., Feng, Z.H., Li, D.J., 2021. Accumulation of microplastics in a downstream area of a semi-enclosed bay: implications of input from coastal currents. Sci. Total Environ. 791, 148280.
Lo, H.S., Xu, X.Y., Wong, C.Y., Cheung, S.G., 2018. Comparisons of microplastic pollution between mudflats and sandy beaches in Hong Kong. Environ. Pollut. 236, 208–217.
Macieira, R.M., Oliveira, L.A.S., Cardozo-Ferreira, G.C., Pimentel, C.R., Andrades, R., Gasparini, J.L., Sarti, F., Chelazzi, D., Cincinelli, A., Gomes, L.C., Giarrizzo, T., 2021. Microplastic and artificial cellulose microfibers ingestion by reef fishes in the Guarapari Islands, southwestern Atlantic. Mar. Pollut. Bull. 167, 112371.
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.
Mishra, A.K., Singh, J., Mishra, P.P., 2021. Microplastics in polar regions: an early warning to the world's pristine ecosystem. Sci. Total Environ. 784, 147149.
Mouchi, V., Chapron, L., Peru, E., Pruski, A.M., Meistertzheim, A.L., Vetion, G., Galand, P.E., Lartaud, F., 2019. Long-term aquaria study suggests species-specific responses of two cold-water corals to macro-and microplastics exposure. Environ. Pollut. 253, 322–329.
Napper, I.E., Davies, B.F.R., Clifford, H., Elvin, S., Koldewey, H.J., Mayewski, P.A., Miner, K.R., Potocki, M., Elmore, A.C., Gajurel, A.P., Thompson, R.C., 2020. Reaching new heights in plastic pollution-preliminary findings of microplastics on mount everest. One Earth 3 (5), 621–630.
Nie, H.Y., Wang, J., Xu, K.H., Huang, Y.J., Yan, M.T., 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.
Pantos, O., 2022. Microplastics: impacts on corals and other reef organisms. Emerging Top. Life Sci. 14, 81–93.
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., da Silva, K.B., 2020. Spatial distribution of microplastics around an inhabited coral island in the Maldives, Indian Ocean. Sci. Total Environ. 748, 141263.
Raguso, C., Saliu, F., Lasagni, M., Galli, P., Clemenza, M., Montano, S., 2022. First detection of microplastics in reef-building corals from a Maldivian atoll. Mar. Pollut. Bull. 180, 113773.
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., Hammer, N., Miller, I.B., Rades, M., Schubert, P., Ziegler, M., Wilke, T., 2022. Reef-building corals act as long-term sink for microplastic. Glob. Chang. Biol. 28 (1), 33–45.
Rillig, M.C., Kim, S.W., Kim, T.Y., Waldman, W.R., 2021. The global plastic toxicity debt. Environ. Sci. Tech. 55 (5), 2717–2719.
Rotjan, R.D., Sharp, K.H., Gauthier, A.E., Yelton, R., Lopez, E.M.B., Carilli, J., Kagan, J. C., Urban-Rich, J., 2019. Patterns, dynamics and consequences of microplastic ingestion by the temperate coral, *Astrangia poculata*. Proc. Roy. Soc. B-Biol. Sci. 286 (1905), 20190726.
Savinelli, B., Fernandez, T.V., Galasso, N.M., D'Anna, G., Pipitone, C., Prada, F., Zenone, A., Badalamenti, F., Musco, L., 2020. Microplastics impair the feeding performance of a Mediterranean habitat-forming coral. Mar. Environ. Res. 155, 104887.
Spalding, M.D., Brown, B.E., 2015. Warm-water coral reefs and climate change. Science 350 (6262), 769–771.

Su, Y.L., Zhang, K.D., Zhou, Z., Wang, J.R., Yang, X.H., Tang, J., Li, H.F., Lin, S.J., 2020. Microplastic exposure represses the growth of endosymbiotic dinoflagellate *Cladocopium goreaui* in culture through affecting its apoptosis and metabolism. Chemosphere 244, 125485.

Tan, F., Yang, H.Q., Xu, X.R., Fang, Z., Xu, H.L., Shi, Q., Zhang, X.Y., Wang, G., Lin, L., Zhou, S.N., Huang, L., Li, H.X., 2020. Microplastic pollution around remote uninhabited coral reefs of Nansha Islands, South China Sea. Sci. Total Environ. 725, 138383.

Tubau, X., Canals, M., Lastras, G., Rayo, X., Rivera, J., Amblas, D., 2015. Marine litter on the floor of deep submarine canyons of the Northwestern Mediterranean Sea: the role of hydrodynamic processes. Prog. Oceanogr. 134, 379–403.

Wang, T., Zou, X.Q., Li, B.J., Yao, Y.L., Zang, Z., Li, Y.L., Yu, W.W., Wang, W.Z., 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.

Wild, C., Hoegh-Guldberg, O., Naumann, M.S., Colombo-Pallotta, M.F., Ateweberhan, M., Fitt, W.K., Iglesias-Prieto, R., Palmer, C., Bythell, J.C., Ortiz, J.C., Loya, Y., van Woesik, R., 2011. Climate change impedes scleractinian corals as primary reef ecosystem engineers. Mar. Freshw. Res. 62 (2), 205–215.

Zhou, Z., Tang, J., Cao, X., Wu, C., Cai, W., Lin, S., 2023. High heterotrophic plasticity of massive coral porites pukoensis contributes to its tolerance to bioaccumulated microplastics. Environ. Sci. Tech. 57 (8), 3391–3401.

Zimmermann, L., Bartosova, Z., Braun, K., Oehlmann, J., Volker, C., Wagner, M., 2021. Plastic products leach chemicals that induce in vitro toxicity under realistic use conditions. Environ. Sci. Tech. 55 (17), 11814–11823.