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Role of Microplastics in Global Warming and Climate Change: A Review

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Abstract Microplastics (MPs) have become an important concern among scientists and policymakers all around the globe. Despite this, the contribution of MPs to global warming and climate change, a significant aspect of the issue, has been overlooked. Continuous greenhouse gas (GHG) emissions resulting in climate change have long been a major issue with apparent consequences. Climate change and plastic crises are threatening our planet, and the co-occurrence of both would be catastrophic. This article addressed the links between microplastic pollution and climate change; how MPs contribute to climate change by interacting with water, air, and soil; and recommendations to address the issues together. Throughout their lives, plastics emit GHG. MPs in water impede the climate change mitigation potential of the ocean in different ways; they hamper photosynthesis and carbon sequestration by phytoplankton and the Blue Carbon Ecosystem. MPs induce GHG emissions from the soil. Airborne MPs have the potential to aid in cloud formation and interfere with atmospheric cooling. Climate change–induced extreme events redistribute MPs in the environment, causing the pollution to increase vertically and horizontally, which then aggravates the situation in a feedback loop. The evidence acquired in the study implies that MPs and climate change are inextricably linked and that MPs play a vital role in fueling climate change. This bridges the gap between MPs and climate change issues that were previously regarded separately. Due to the linkages between these

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intertwined challenges, integrated and holistic research and policy measures are required to address both crises concurrently.

Keywords Plastic pollution · Greenhouse gases · Ocean · Blue carbon · Carbon sequestration

1 Introduction

Plastics have become an inseparable part of modern life, possessing several excellent properties that have allowed them to replace a variety of naturally derived materials (Hale et al., 2020; Lebreton & Andrady, 2019). Although the plastics industry dates back to the early 1900s, mass manufacture of plastics did not begin until the 1950s; since then, about nine billion metric tons of plastic materials have been manufactured globally (Tiseo, 2021). After plastics are used, a considerable amount becomes waste and leaks into the environment when inappropriately dumped or mismanaged. Once discharged into the environment, plastics degrade due to a variety of factors, including solar radiation, mechanical forces, and microbiological action, resulting in the creation of smaller pieces (Fernández-González et al., 2021; Gong & Xie, 2020; Zhang et al., 2021). The degradation of plastics produces a tremendous quantity of microplastics (MPs) and nanoplastics (NPs) in the environment over time (Ainali et al., 2021; Chowdhury et al., 2023; Kakar et al., 2023; Peng et al., 2017). Scientists detected the presence of tiny microplastic particles in the ocean in the 1970s (Carpenter & Smith, 1972; Carpenter et al., 1972). Although microplastic particles are now widely recognized as ubiquitous in the environment, research into their distribution and impact did not effectively begin until 2004 (Rochman, 2018). In recent decades, microplastic pollution has become a major source of concern among scientists, policymakers, and people all around the globe (Hakim et al., 2023; Mahmud et al., 2022; Silva et al., 2018).

Despite growing concern about the occurrence, source, distribution, and effects of MPs on marine, freshwater, and terrestrial ecosystems, a very significant aspect of the crisis, namely, the contribution of MPs to greenhouse gas (GHG) emissions, has been overlooked. There is a considerable knowledge gap on the connections between MPs and global warming and climate change, particularly on the role of MPs in global warming and climate change. Usually, the issues of MPs and climate change are traditionally considered separate. Even the group of scientists and policymakers working distinctively on microplastic pollution and climate change seem to compete against each other for funding attention and policy implications. However, both the climate change and plastic pollution crises are threatening our planet, and the co-occurrence of both would be dangerous. Much is yet to be achieved on this challenging topic, providing us with a reason to initiate the current study. Therefore, in this study, we aim to explore the multifaceted connections between microplastic pollution and climate change and provide remedies to address both. Although several authors (Ford et al., 2022; Shen et al., 2020a) recently attempted to discuss the link between microplastic pollution and climate change, they focused on certain aspects that are only just beginning to be completely understood. Conversely, the current research covered more aspects of the connection between microplastic pollution and climate change in depth, with greater evidence from aquatic ecosystems, the terrestrial environment, and the atmosphere (Fig. 1). From the evidence gathered, one can infer that microplastic pollution plays a significant role in global warming and climate change and that MPs and climate change issues are inextricably linked. As a result, the current article bridges the gap between MPs and climate change challenges that were previously regarded separately. We also suggested some important research and policy implications for effective and sustainable solutions to tackle these complex, intertwined global challenges.

In addition to being a major source of pollution, plastics also accelerate global warming and climate change. However, global carbon budgets and modeled future projections are not taking this fact into account. Earth's climate is changing faster than scientists had ever expected (Tollefson, 2022). GHG emissions continue to rise, prolonging global warming and causing cascading impacts via other major climate factors, all of which contribute to the occurrence of high-impact severe events around the world (WMO, 2022). The average surface temperature of Earth in 2021 was 1.04 °C warmer than the pre-industrial average and 0.84 °C warmer than the average temperature in the twentieth century (Lindsey & Dahlman, 2021). The estimated global mean temperature in 2022 was about 1.15 °C above the pre-industrial (1850–1900) average

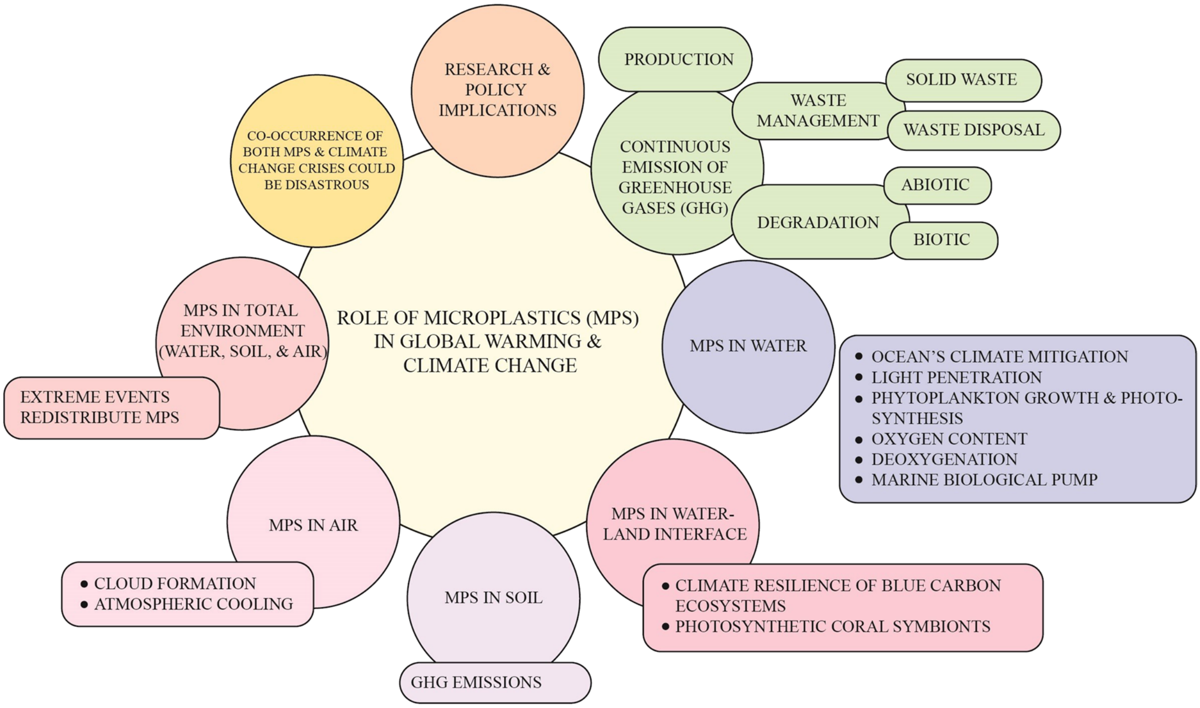

Fig. 1 An overview of the role of MPs in global warming and climate change

(WMO, 2022), and if it rises by more than 1.5 °C, the environmental implications would be disastrous (Tollefson, 2022). The probability of global warming approaching or exceeding 1.5 °C within the next few decades is greater than 50%. As a result, people and ecosystems will inevitably face the risk of many climatic hazards (IPCC, 2022). Each of us already knows and has seen many examples of how global warming and climate change can impact the environment, for example, through increased temperature and ocean acidification (Bijma et al., 2013; Mendler de Suarez et al., 2014; Reid et al., 2009). Several authors have also reported on negative effects that the co-occurrence of climate change and microplastic pollution are having on a variety of organisms (Bertucci et al., 2022; Bertucci & Bellas, 2021; Firmino et al., 2022; Kratina et al., 2019; Wang et al., 2020). Both climate change and plastic pollution crises are threatening our globe right now, and if they strike simultaneously in aquatic environments, the results might be disastrous (Ford et al., 2022).

The primary question of the current work is as follows: do MPs fuel global warming and climate change? We hypothesized that microplastic pollution and climate change are inextricably linked and fuel global warming and climate change, and we provided evidence supporting the hypothesis. First, plastics release different greenhouse gases and other harmful gases from cradle to grave. The emission of GHG continues from the extraction and shipping of raw materials to the production phase as well as waste disposal processes and even long after the plastic has been discarded, literally at every stage of its life cycle (Ford et al., 2022; Zheng & Suh, 2019). Second, MPs hinder the ocean's climate mitigation potential in many different ways. World oceans are the greatest carbon sink (Armstrong McKay et al., 2021; Findlay & Turley, 2021; Shen et al., 2020b) and oxygen (O_2) producers (Borisov & Björn, 2018; Sekerci & Petrovskii, 2015) on the planet, playing a very crucial role in regulating the climate. Currently, between 1.15 and 2.41 million tons of plastic debris reach the ocean per year (Lebreton et al., 2017), which will presumably be raised by a factor of ten over the next 10 years (Romera-Castillo et al., 2018). MPs prevailing in the air and the water decrease the penetration of light in the water column through reflection, scattering, and absorption of incoming solar radiation. They interfere with the overall metabolism, growth, development, and photosynthesis efficiency of phytoplankton. MPs, like any other floating object in the ocean, attract microorganisms that congregate around and colonize plastic floating in the water, forming a thin layer of life called biofilm, known as the plastisphere (Battulga et al., 2022). Increased activity by the plastisphere microbial community and ingestion of MPs by zooplankton reduce the oxygen content of water, inducing deoxygenation in the ocean. MPs also seriously affect the marine biological carbon pump through slower organic and fecal material sinking, which would have a cascade effect on carbon dioxide (CO_2) cycling and global carbon flux. Third, MPs interfere with the growth, photosynthesis, and overall carbon sequestration efficiency as well as other climate services of the Blue Carbon Ecosystems (BCE). Fourth, MPs impair the carbon and nitrogen cycling in the soils and induce the emission of GHG from the soils. Furthermore, atmospheric MPs contribute to cloud formation and inhibit atmospheric cooling. Conversely, climate change–driven extreme events spread and redistribute MPs, facilitating the prevalence of MPs in the environment. The events aggravate the microplastic pollution impacts at the next level, working in a loop.

Microplastic pollution and climate change, both of which are among the most important issues confronting the globe today, are typically considered separate, even though they are inextricably related (Bergmann et al., 2022; Ford et al., 2022; Haque & Fan, 2023; Kakar et al., 2023; Shen et al., 2020a; Stoett & Vince, 2019). Therefore, there is a need to integrate the concepts and efforts that relate to microplastic pollution and climate change. To combat both crises simultaneously, it is essential to develop integrated and holistic approaches to research and policy implications.

2 Methodology

This article provides a detailed review of the link and interaction between MPs and climate change, covering a range of key literature concerning microplastic pollution in different environmental matrices. The following section describes the two main steps of our study: identification of relevant literature and categorization of studies under our research questions. Using Boolean operators, we conducted a literature search based on our primary research question and with the following databases: Scopus, Web of Science, and PubMed. The combination of phrases and keywords used were (“microplastics”) AND (“greenhouse gas” OR “global warming” OR “climate change”). The search yielded 275 results in Scopus, 397 results in Web of Science, and 177 results in PubMed (total = 849 results). Also, the literature was supplemented with a search of gray literature, such as policy documents, reports, and available science-based portals. Backward searches were also performed by checking citations on reference lists of selected articles meeting similar criteria. Based on our exclusion criteria, we then narrowed the collected literature that relates directly to microplastic pollution and climate change through an inspection of the articles and by removing the duplicates. The bibliometric data of the literature was processed in the VOSviewer software. The occurrences of the keywords were shown on the maps as network visualization, where the size of the label and the circle are determined by their weight (Fig. 2).

We then categorized articles based on their relevance to the emissions of different greenhouse gases and other harmful gases, for example, in the life cycle from cradle to grave. We worked on this section in three main phases of the end-of-life cycles of plastics, starting from the production, waste disposal processes (landfilling, recycling, and incineration), and degradation of plastics in the environment. Secondly, we reviewed the pathways by which microplastic pollution hinders the ocean’s climate mitigation potential by affecting different aspects of the ocean’s ecosystem services and resilience to global warming and climate change. Covered here were different important aspects such as the alteration of the incoming solar radiation (through reflection, scattering, and absorption) in the water column; interference with the overall metabolism, growth, development, and photosynthesis efficiency of phytoplankton; reduction in the O_2 content of water by the plastisphere (through increased bacterial activity); deoxygenation through consumption of MPs by zooplankton; and the impact on the marine biological pump (through slower organic and fecal material sinking). Thirdly, the BCE is taken into consideration to investigate the impacts of MPs on their O_2 generation and carbon sequestration, as well as other climate services. Afterward, the role of MPs in the emission of GHG from the soil ecosystem and their interaction with the

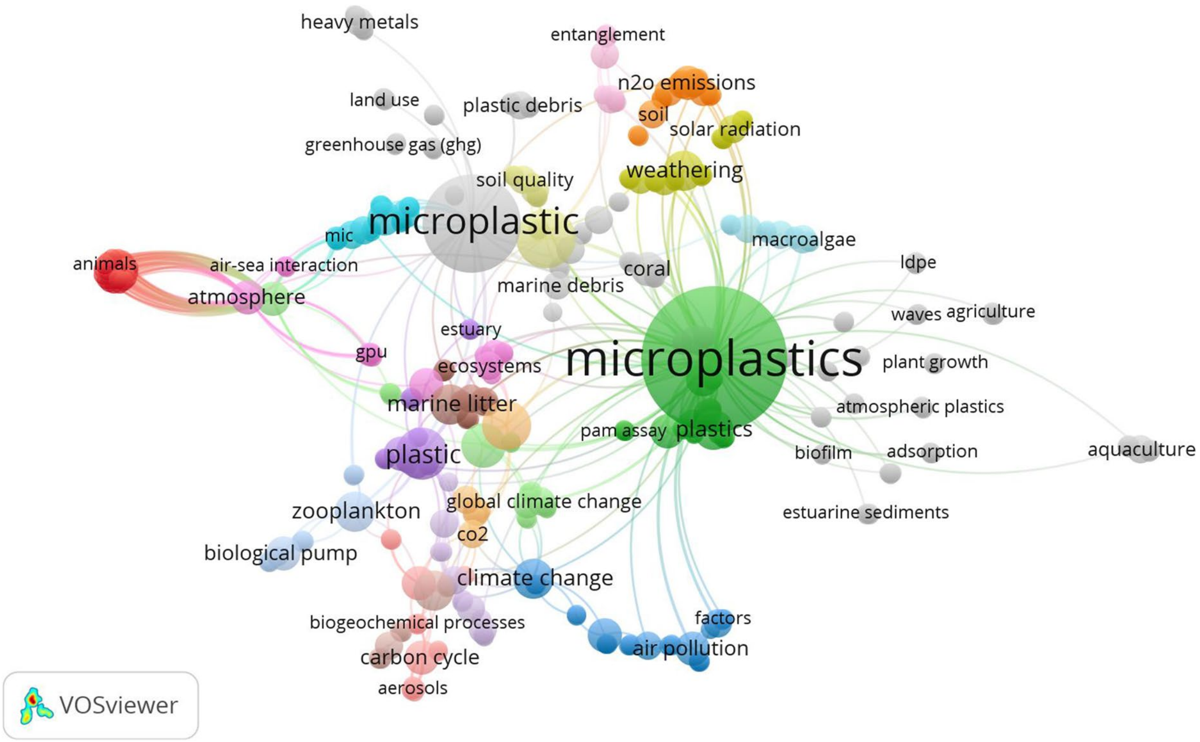

Fig. 2 Network visualization generated in VOSviewer

atmosphere are studied. Furthermore, the effects of climate change–driven extreme events on microplastic pollution and the co-occurrence of both climate change and plastic pollution crises are addressed.

3 Continuous Emissions of Greenhouse Gases by Plastics

3.1 During Production Processes

The plastics industry is one of the fastest-growing and most GHG-intensive industries, producing billions of tons of GHG (An et al., 2022; Shen et al., 2020a). Traditionally, plastics are made from fossil fuels such as natural oil and gas (Chamas et al., 2020; Geyer et al., 2017; Hamilton et al., 2019; Mulder, 1998). Production of plastics utilizes about 4% of the world's nonrenewable oil and gas as raw materials and an additional 3–4% as energy in the manufacturing processes (Hopewell et al., 2009). Greenhouse gases are generated throughout the extraction, shipping, production of plastics and even long after they have been discarded, literally at every stage (Fig. 3) of their life cycle (Ford et al., 2022; Kakar et al., 2023). The extraction and transportation of fossil fuels contribute to GHG emissions both directly and indirectly through leaching, emissions from fuel use in the process, and emissions generated by land cover change for the construction of extraction infrastructure (Hamilton et al., 2019). The chemical processes used to refine fuels and make plastics also generate large emissions during polymerization, plasticization, and other steps (Hamilton et al., 2019). For example, only polyvinyl chloride (PVC) plastic produces 7.83 kg CO_2-equivalent (CO_2e) of greenhouse gas emissions in total throughout the manufacturing stage (Liang & Yu, 2023). According to recent scientific studies, the plastics industry is a major contributor to global warming, responsible for roughly 4% of worldwide GHG emissions (Zheng & Suh, 2019). Plastic industries released more than 850 million metric tons of GHG into the environment in 2019, which is equal to 189 coal-fired power plants (Hamilton et al., 2019). The global life cycle GHG emissions from traditional plastic materials were 1.7 Gt of CO_2e in 2015, and

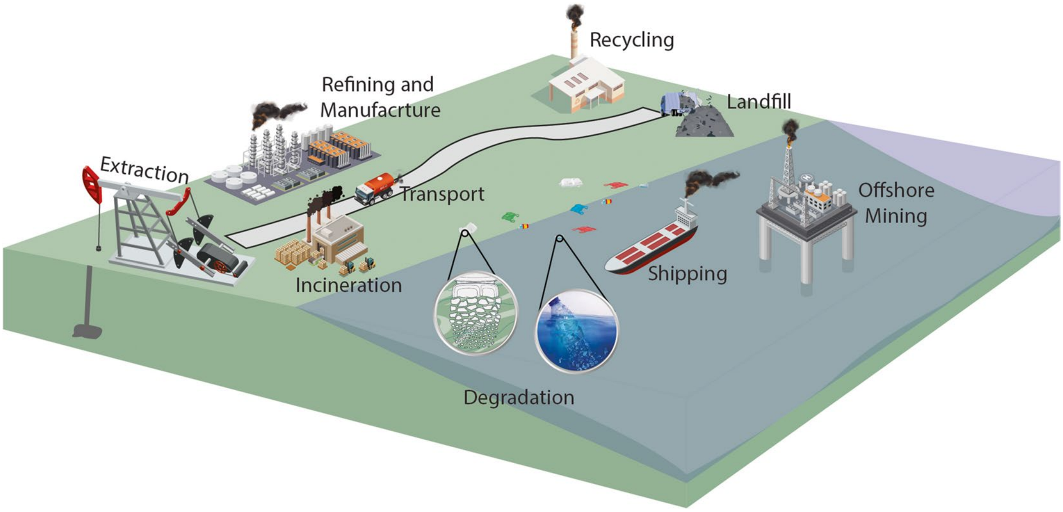

Fig. 3 Plastics release different greenhouse gases at every stage of their life cycle

if current trends continue, they will rise to 6.5 Gt of CO_2e by 2050 (Zheng & Suh, 2019). We can all see that GHG is already increasing global temperatures, melting ice caps, and raising sea levels, thus threatening lowlands and the lives of millions of people all around the globe. Even more worrying, predictions do not indicate that the emission of harmful gases from plastic processes into the atmosphere will be reduced in the near future. Rather, the emissions are projected to increase in the years ahead, meaning that they will soon be a greater contributor to global warming and climate change than previously. Global production of plastics has already increased fourfold over the past four decades, and if current trends hold, the generation of GHG from plastics will account for 15% of the world's carbon budget by 2050 (Geyer et al., 2017; World Economic Forum, 2016). In addition to emitting GHG, the production of plastics affects socioeconomic and health factors, as with particulate matter emissions and the employment of laborers (Cabernard et al., 2022).

3.2 In the Course of Waste Management

3.2.1 Microplastics in Solid Waste

Continuous economic progress and urbanization are being accompanied by a growing flow of solid waste. Every day, modern society produces a massive amount of solid waste, of which plastics make up a sizable portion (Napper & Thompson, 2020). Improper management of solid waste, particularly municipal solid waste (MSW), has become a critical issue, posing a substantial environmental burden globally (Huynh et al., 2023). MSW has a multitude of detrimental environmental effects, including nitrogen pollution, GHG emissions, and plastic deposition in the ocean (Chen et al., 2020a, 2020b). Solid waste has a reputation of the worst kind for releasing different hazardous gases, such as hydrogen sulfide, methane (CH_4), and ammonia (NH_3) (Al-Omar et al., 1987). However, GHG emissions are one of the most serious environmental repercussions of this waste sector (Wünsch & Tsybina, 2022). Traditionally considered the ultimate option for disposing of solid waste, landfilling produces significant volumes of different greenhouse gases, including CH_4, in addition to other pollutants (Muenmee et al., 2016). MSW serves as an essential microplastic store and contributes significantly to further contamination in different ecosystems (Shi et al., 2023; Zhou et al., 2023). He et al. (2019) detected 17 different types of plastics in landfill leachate and concluded that MSW landfills are important sources of MPs. MSW landfills have recently been noted as important suppliers of MPs and NPs in the environment (Petrović et al., 2023). Priya et al. (2023) reported the leachate from solid waste dumps as the primary source of MPs in groundwater. Anupama et al. (2022) stated that there were 178 fragments of MPs per 100 g of topsoil in a waste disposal yard. An assessment of the microplastic particle abundance in the soil from an open-solid waste landfill revealed 180–1120 microplastic particles per kilogram of soil (Mahesh et al., 2023). Microplastic particles might transform into NPs, which could fly away as wind-blown particles. Li et al. (2020) reported airborne fiber particles in the urban atmosphere, predominated by MPs along with man-made mineral fibers. These MPs will pollute the environment in their immediate vicinity and impair the functions of different ecosystems, leading to global warming along with other impacts. For example, a river that borders a waste disposal site was found to be contaminated with an average of 100 microplastic fragments per 100 g of sediment (Anupama et al., 2022). Additionally, MPs are not often isolated contaminants in MSW landfills but instead absorb a variety of hazardous substances and act as significant conduits for other pollutants, exacerbating the negative effects (Golwala et al., 2021; Shi et al., 2023). However, sustainable MSW management practices, such as composting with MSW separation at the source, have the potential to lessen the dangers associated with landfilling or, worse, open burning or dumping (Huynh et al., 2023).

3.2.2 *Waste Disposal Processes*

Plastics are present in almost all waste, accounting for approximately10% of the rubbish discarded by mass production (Barnes et al., 2009). Considering the extremely light weight of plastics compared to other objects found in trash, the volume is quite huge. Landfilling, recycling, and incineration of garbage into usable commodities are some of the most common alternatives in any waste disposal and management process (Rebeiz & Craft, 1995). Plastic waste, whether recycled, burned in incinerators, or dumped in landfills, releases GHG (Fig. 3) and harms the environment (Chow et al., 2017; Hamilton et al., 2019). Plastic waste production has skyrocketed due to greater reliance on plastics in tandem with global economic expansion (Chow et al., 2017; Miranda et al., 2021; Worm et al., 2017). As a result, the environmental consequences that stem from the subsequent disposal of plastic waste have become a growing concern. Of the 25.8 million tons of plastic waste produced annually in Europe, less than 30% is recycled, 31% is stored in landfills, and 39% is burned (Drzyzga & Prieto, 2019). Large amounts of GHG, such as CH_4, and other pollutants are produced during landfilling (Muenmee et al., 2016). Although landfilling produces fewer greenhouse emissions in absolute terms, it poses serious additional risks, such as polluting soil and water (Hamilton et al., 2019). Landfills can also be a source for plastics to spread further into surrounding areas through leachates and erosion (Hale et al., 2020) and into the atmosphere as wind-blown particles (Barnes et al., 2009). Landfills are considered significant contributors of MPs and NPs in the air (Petrović et al., 2023). Liang and Yu (2023) reported that the recycling phase of PVC waste plastic generates 0.345 kg CO_2-e. Although recycling is considered to have a moderate carbon footprint (Hamilton et al., 2019), it requires infrastructure and instrument sets that consume energy. The incineration of plastic waste results in a net positive CO_2emission (Pilz, 2014). In addition to generating CO_2, incineration produces particulate matter, nitrogen oxides, carbon monoxide, and volatile organic compounds (Ali et al., 2021). However, of all plastic waste disposal methods, incineration produces the most emissions, making it the principal offender in the gang-damaging environment (Hamilton et al., 2019; Wollny et al., 2001). Greenhouse gases are also produced in a sizable amount during the road transportation of untreated trash (Rem et al., 2009). Inappropriate and careless handling during collection and transportation can also leak plastics into the environment (Barnes et al., 2009). Furthermore, existing waste disposal facilities are not adequate in capacity to handle the continually increasing quantities of plastic waste produced around the globe; nevertheless, a large portion of spent plastic enters the environment as macro- and microplastics, causing varying ramifications (Koller et al., 2023).

3.3 Throughout Degradation in the Environment

3.3.1 *Abiotic Degradation*

All plastics manufactured worldwide are not managed through systematic waste disposal systems. Consequently, large quantities of manufactured plastics are discarded in the environment (Fig. 3). Ineffective and, in some cases, insufficient waste management contributes to the release of a significant amount of plastic into the environment (Barnes et al., 2009). Additionally, irresponsible human behavior, such as not using trash bins or disposing of trash far from collection points, contributes to the problem. Generally, polymers exposed to the environment face polymer chain breakup through photo-oxidative degradation by solar radiation (Ainali et al., 2021). In the environment, plastics become fragile as time passes and degrade into small to smaller pieces through a variety of different processes, including chemical oxidation, mechanical weathering, and microbiological action (Fernández-González et al., 2021; Gong & Xie, 2020; Weinstein et al., 2016; Zhang et al., 2021). While plastics are susceptible to weathering to variable degrees depending on the duration and intensity of the influencing stimuli, photo-oxidation occurs most quickly when plastics are on the surface of water, on beaches, and on land (Delre et al., 2023; Hale et al., 2020). This fragmentation produces massive quantities of MPs and NPs in the environment as the particle size keeps decreasing over time (Ainali et al., 2021; Hale et al., 2020; Kakar et al., 2023; Peng et al., 2017). Much of the MPs and NPs in the environment today are thought to have originated from this process. These plastics perpetually emit different greenhouse gases, such as CO_2, CH_4, ethylene, and other chemicals, while they degrade in nature (Kida et al., 2022; Royer et al., 2018). MPs in the environment also change their characteristics over time, influencing their behavior and amplifying their impacts (Miranda et al., 2021). MPs will transform into small to smaller sizes as they are very persistent. Kida et al. (2022) analyzed the effect of microplastic particle size on the amount of CO_2 and CH_4 emissions and found that the smaller the particles, the higher the emission. Additionally, plastics in the aquatic environment also leak various toxic compounds into the water at a higher rate as their qualities change with aging (Bandow et al., 2017). Still, the process is not fully understood, and there is much ambiguity about the environmental consequences of the deterioration of MPs under diverse stimuli (Sun et al., 2020).

3.3.2 Biotic Degradation

Because of the continuous mounting of plastic production and the overwhelming burden on waste disposal facilities, the necessity for biodegradable plastics and the biodegradation of plastic waste has gained importance in recent years (Zheng et al., 2005). Plastics eventually undergo degradation and turn into MPs, and MPs also break down into ever-tinier particles that are sub-micrometer in size, for example, NPs (Rani-Borges et al., 2023). In the environment, MPs degrade into smaller particles, such as NPs, through both abiotic and biotic processes (Sutkar et al., 2023). Even though plastics are persistent, many plastic-degrading enzymes and bacteria have evolved (Dunn & Welden, 2023). Various microbes occupy the ecological niche created by the MPs following the breakdown of plastic products (Gilani et al., 2023). The main groups of synthetic plastics associated with biotic degradation, or biodegradation, are nylon, polystyrene, polypropylene polyurethane polyethylene, and polyethylene terephthalate (Amobonye et al., 2021; Andler et al., 2022). Biodegradation of plastics is performed by different organisms, particularly microorganisms, both in aerobic and anaerobic conditions. In recent years, it has been demonstrated that a variety of species play a role in the breakdown of plastics. Yet, the quantity of these organisms remains limited, and the rates of degradation are very slow, assuming that degradation occurs at all in various environmental systems—a question that is currently being investigated (Andler et al., 2022; Koller et al., 2023). CH_4 and CO_2 are generated during plastic biodegradation (Ali et al., 2021; Gilani et al., 2023; Müller, 2005; Zeenat et al., 2021; Zhang et al., 2021). Each of these gases is a strong heat-trapping gas, or GHG, responsible for global warming and climate change. Thus, the biotic degradation of plastics also contributes to global warming and climate change. Furthermore, instead of mineralizing MPs, biodegradation usually results in the fragmentation of MPs into smaller particles, which may still exist in nature and have further impacts through unanticipated cascades of processes (Sutkar et al., 2023).

4 Microplastics in Water: Microplastics Hinder the Ocean's Climate Change Mitigation Potential

Water, especially oceanic and marine water, covers the majority of the Earth's surface. MPs are found in all bodies of water (Supplementary Information Table 1). The world's oceans play a crucial role in maintaining a stable climate by significantly contributing to the global carbon cycle, in addition to exchanging heat, water, momentum, particles, and other substances with the atmosphere (Bigg et al., 2003; Mendler de Suarez et al., 2014). The oceans are the top producers of O_2 (Borisov & Björn, 2018; Sekerci & Petrovskii, 2015) and are the largest carbon sink (Armstrong McKay et al., 2021; Findlay & Turley, 2021; Shen et al., 2020b) on the planet. Oceans safeguard the Earth from the most detrimental impacts of climate change by absorbing and neutralizing rising CO_2 and other greenhouse gases from the atmosphere (Bijma et al., 2013; Reid et al., 2009). They have a magnificent capability to absorb CO_2 and have already absorbed around one-fourth to one-third of the CO_2 released into the atmosphere by human activity (Findlay & Turley, 2021). However, MPs impede the ocean's incredible climate change mitigation capacity and climate resilience in a variety of ways, such as inhibiting light penetration in the water column, interfering with the growth and photosynthesis efficiency of phytoplankton, reducing the oxygen content in water, fueling deoxygenation in the ocean, and affecting the marine biological carbon pump.

4.1 Microplastics Inhibit Light Penetration in the Water Column

MPs are often less dense than seawater, allowing them to float on the ocean surface, resulting in higher quantities of the sea surface microlayer (Anderson et al., 2018; Bain, 2022). MPs floating on the ocean surface can change the rate of reflection and absorption of the incoming solar radiation in the water column (Fig. 6). Any floating material having more optical density than water might change the optical properties of surface waters. MPs floating on the ocean surface are composed of different polymers and greatly vary in color. MPs, especially those with dark colors (e.g., black, gray, or brown), would, therefore, absorb solar radiation. Moreover, each particle may host a distinct combination of bacteria, viruses, and algae in its plastisphere, leading to a huge variation in the optical properties of surface water, which may alter the surface albedos. Airborne MPs were recently envisaged as significant light-absorbing particles that would impact albedos in the cryosphere (Fig. 6) through positive net radiative forcing (Zhang et al., 2022). MPs can influence the cooling or warming of water by scattering and attenuating the shortwave radiation from the sun, thereby changing other physicochemical properties of the water column (VishnuRadhan et al., 2019).

Revell et al. (2021) quantified the optical properties and potential direct radiative effects of atmospheric MPs to influence Earth's climate by absorbing and scattering radiation. However, VishnuRadhan et al. (2019) raised the novel idea that by altering the incoming radiation from the sun, plastics can change physical processes in the ocean water column and influence the global climate cycles. However, we are still not concerned enough about the issue, which may be attributable to the fact that plastics have not yet had a discernable effect on the Earth's climate cycles. An effect may occur in the upcoming decades given that in some areas of the ocean, plastics have already reached high concentrations.

4.2 Microplastics Interfere with the Growth and Photosynthesis Efficiency of Phytoplankton

Although its global biomass is small, phytoplankton plays a key role in aquatic primary production and Earth's climate (Uwizeye et al., 2021). These tiny organisms are among the most efficient photoautotrophs in the ocean, sequestering a large portion of atmospheric CO_2 into the ocean's interior via photosynthesis and the carbon pump (Pierella Karlusich et al., 2021). Phytoplankton contributes approximately80% of the Earth's entire O_2 production and almost half of the global carbon fixation through photosynthesis (Käse & Geuer, 2018; Sekerci & Petrovskii, 2015; Shen et al., 2020b). The organisms could incorporate approximately 45–50 billion tons of inorganic carbon into their cells by absorbing CO_2 that would otherwise dissolve in the water and make it more acidic (Falkowski, 2012). A large volume of MPs floating in the world's oceans could reduce light transmission, lowering phytoplankton growth and photosynthetic efficiency (Shen et al., 2020b). Plastic particle attachment could prevent light from reaching the photosynthetic centers, resulting in reduced photosynthesis, and could also rupture the cell wall, leading to the creation of holes and the absorption of particles by phytoplankton (Bhattacharya et al., 2010; Kakar et al., 2023).

MPs have toxic effects on phytoplankton, affecting growth, gene expression, morphology, and colony size and limiting overall photosynthesis efficiency (Supplementary Information Table 2) through interactions with compounds linked with plastics or adsorbed pollutants (Nava & Leoni, 2021; Yokota et al., 2017). The proliferation of cells, concentration of chlorophyll-a, and photosynthetic efficiency of *Phaeodactylum tricornutum* were decreased by 53.53%, 25.45%, and 12.50%, respectively, by polystyrene (PS) microplastic (Lang et al., 2022). PS particles decreased the growth of phytoplankton *Dunaliella tertiolecta* by as much as 45% at high concentrations, and these negative effects were shown to worsen with finer particles (Sjollema et al., 2016). PS nanoparticles reduced the content of chlorophyll production and impeded the growth and development of phytoplankton *Scenedesmus (S.) obliquus* in experimental exposure (Besseling et al., 2014). PVC-type MPs had serious negative effects on the growth and photosynthesis of marine phytoplankton *Skeletonema costatum* (Zhang et al., 2017). Polypropylene (PP) and PVC hindered photosynthesis in *Chlorella (C.) pyrenoidosa* and *Microcystis (M.) flos-aquae* (Wu et al., 2019). Ansari et al. (2021) reported up to 42.7%, 41.6%, and 37.7% growth inhibition of *Acutodesmus (A.) obliquus* by polyethylene (PE), PVC, and PP, respectively, along with decreased photosynthetic efficiency in high exposure to MPs. MPs of polyethylene terephthalate had a strong negative influence on the growth, chlorophyll content, and toxicity of *Scenedesmus* sp., with the effects becoming more severe at higher concentrations (200 mg/L) (Khatiwada et al., 2023). Strong negative effects were seen on the growth and photosynthesis of the microalgae *S. vacuolatus* by the MPs produced from an additive including electronic trash and a computer keyboard (Rummel et al., 2022). MPs stunted the growth of *S. obliquus* by 50% through light obstruction and, in some cases, hampered the cell wall for attachment to the algal body (Liu et al., 2020). Adsorption of plastic beads inhibited the photosynthesis of *Chlorella* and *Scenedesmus*, presumably due to the nanoparticles physically blocking light and air movement (Bhattacharya et al., 2010).

MPs could also alter the metabolism and decrease the protein content of phytoplankton at higher concentrations (Ansari et al., 2021). For example, protein content in microalgae was shown to drop considerably at higher microplastic concentrations in microalga *A. obliquus* (Ansari et al., 2021). Nylon MPs were also reported to destroy cell membranes, enhance the release of extra-membranous substances, reduce phycobili proteins synthesis, and induce oxidative stress along with photosynthesis obstruction and up to 47.62% growth inhibition in *M. aeruginosa* (Zheng et al., 2022). Elevated levels of MPs can also change the overall structure of phytoplankton communities (Hitchcock, 2022). Furthermore, a large number of different plasticizers and additives are added to plastics during manufacturing to increase their flexibility and durability. These plasticizers coexisting in the environment with the MPs also inhibit the growth and photosynthesis of different phytoplankton (Supplementary Information Table 2). For example, diethyl phthalate (DEP) slowed the growth rate of *C. pyrenoidosa*, and algal development was inhibited more severely with the increase in microplastic levels, as demonstrated both by the number of cells and chlorophyll contents (Wenchao et al., 2023). DEP and dimethyl phthalate greatly decreased photosynthesis and chlorophyll-a production of *Phaeodactylum tricornutum* (Gao et al., 2021a, 2021b). Dibutyl phthalate, a different plasticizer, was shown to be hazardous to *S. obliquus*, lowering its development by up to 51.1% at 60 mg/L (Kuang et al., 2003). As a whole, microplastic pollution severely affects the climate mitigation power of the oceans by interfering with phytoplankton's overall community composition, metabolism, growth, development, and photosynthesis efficiency. Such inhibitions are linked to the concentration and particle size of MPs, which have been found to increase at larger concentrations and smaller particle sizes, respectively (Ansari et al., 2021; Liu et al., 2020; Miloloža et al., 2021; Wu et al., 2019; Zheng et al., 2022). Therefore, the tragic irony is that these negative effects will continue to be more severe over time, with the MPs growing in concentration from continuous input and becoming smaller in size because of degradation from their long-time exposure to the environment.

4.3 Plastisphere Reduces the Oxygen Content in Water

MPs in the water provide additional surfaces that serve as an excellent platform for the colonization of distinct microbial communities in the plastisphere (Bowley et al., 2021). Organisms benefit from this surface attachment in many different ways, including enhanced nutritional availability, physical defense, and environmental stability (Hale et al., 2020).

Therefore, a large number of organisms can colonize the surface of a relatively small particle through biofouling processes (Nava et al., 2021). Recent investigations revealed that several forms of plastic submerged in water leached organic carbon molecules, which in turn fueled microbial development in a lab setting (Romera-Castillo et al., 2018). Microplastic particles retrieved from the sea surface had a rich microbiological community including heterotrophs, autotrophs, predators, and symbionts, implying that MPs offer a unique ecological niche in water (Zettler et al., 2013). Thus, by providing home and shelter to a new opportunistic microbial community in the surface water, the plastisphere boosts bacterial activity and organic matter formation (Rummel et al., 2017; Yang et al., 2020). Paluselli et al. (2019) also found a significant increase in different compounds, such as di-isobutyl phthalate and di-n-butyl phthalate, leached from plastics into water. As a result, the amount of chemical compounds on the water surface increases through bacterial production, thus decreasing the O_2 content of the water (Galgani & Loiselle, 2019). MPs form a distinct microbial niche, which may also hinder ecosystem function by encouraging the establishment of some specific microbial populations (Ahmad et al., 2020). For instance, alterations to the surface characteristics of MPs and their interactions with other pollutants result from microbial colonization on MPs in aquatic media (Battulga et al., 2022). When bacteria adhering to MPs interact with each other in seawater, a variety of other fascinating events ensue (Wang et al., 2022a, 2022b).

4.4 Ingestion of Microplastics by Zooplankton Leads to Deoxygenation in the Ocean

Zooplankton are primary consumers in the aquatic environment. As MPs are ubiquitous in oceans, zooplankton ingests MPs together with other foodstuffs. Ingestion of MPs replaces the natural foodstuffs consumed by zooplankton and reduces the uptake of phytoplankton. Reduced grazing pressure on phytoplankton could result in increased algal blooms, which would have significant biological repercussions, almost having the same influence as climate change on ocean O_2 levels (Kvale et al., 2021). In areas where surface macronutrients are abundant, such reduced consumption drives more phytoplankton biomass to be transferred as dropping litter, which utilizes O_2 and recycles micronutrients at depth via remineralization (Kvale et al., 2021). Traditionally, bacteria play a very significant role as remineralizers, converting organic matter to inorganic matter and recycling nutrients (Azam et al., 1983). Thus, the uptake of MPs by zooplankton has the potential to accelerate widespread deoxygenation in the ocean (Kvale & Oschlies, 2022). Kvale et al. (2021) estimated that such increased remineralization can decrease the O_2 content in water by as much as 10% in the North Pacific and reduce worldwide O_2 by an additional 0.2–0.5% compared to 1960 values.

4.5 Microplastics Affect the Marine Biological Carbon Pump

Fish, zooplankton, and other ocean-dwelling animals excrete fecal materials that sink to the ocean floor, which plays a significant role in exporting carbon from surface waters and contributing to global carbon flux (Fig. 4). The marine biological carbon pump facilitates the sinking of biogenic matter that has been assimilated from inorganic CO_2 through photosynthesis and, subsequently, stored far from the atmosphere into the deep ocean (Archer & Jokulsdottir, 2013; De La Rocha & Passow, 2013). Thus, excrement sinking to the ocean floor drives a considerable amount of carbon export from the surface waters, contributing to global carbon flux. The carbon pump is essential for the net transfer of atmospheric CO_2 to the sea waters and eventually to sediments, which keeps the level of CO_2 far lower in the atmosphere than it otherwise would be (Basu & Mackey, 2018). Also, the carbon pump has had an impact on atmospheric CO_2 and deep sea O_2 levels (Emerson & Yang, 2022). The pump exports 5–20 Gt of organic carbon to the deep ocean per year, where 0.2–0.5 Gt of the organic carbon is kept buried for several millennia (Guidi et al., 2015; Henson et al., 2011). The transportation of such a massive amount of CO_2 fixed through photosynthetic processes into the deep ocean controls the Earth's carbon cycle (Le Moigne, 2019).

A wide variety of aquatic animals ingest microplastic particles from water either intentionally or unintentionally (Engler, 2012; Moore et al., 2011). MPs are often mistakenly consumed as foodstuffs, especially when they resemble their typical food items in size and/or shape (Coppock et al., 2019; Moore et al., 2011; Stoett & Vince, 2019). The smaller the particles, the more likely it is that they will be ingested by organisms either

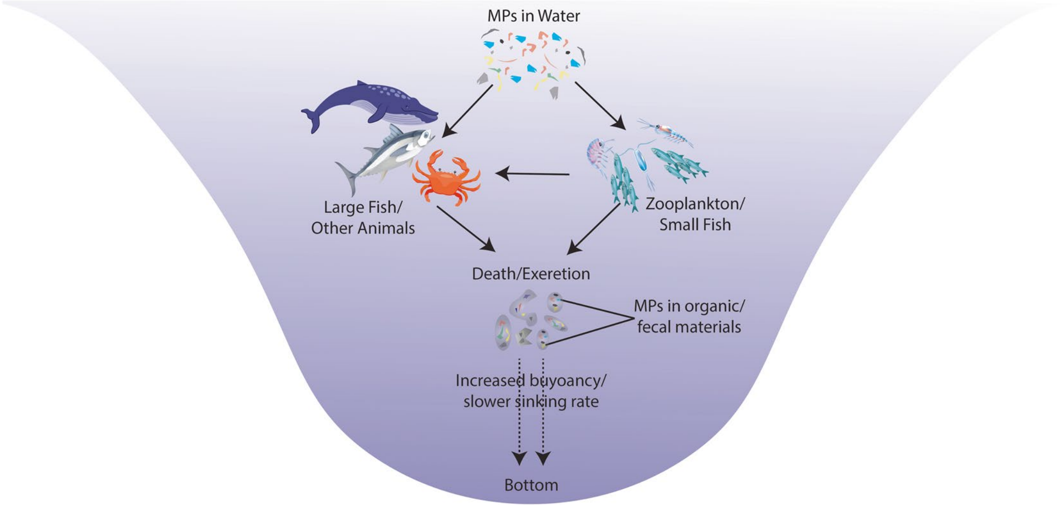

Fig. 4 Pollution from MPs affects the biological carbon pump in the ocean

actively or passively (Botterell et al., 2022; Lehtiniemi et al., 2018). Copepods are among the most prevalent creatures in the ocean, making a very significant contribution to the world's biochemical processes (Xu et al., 2022a, 2022b). They constitute a crucial component of the marine carbon pump through the conveyance of biogenic materials by producing fecal pellets (Torres, 2022). After ingestion, a sizeable portion of these ingested MPs remain in the animal feces, which are naturally expelled by a variety of aquatic species (Duis & Coors, 2016). Nearly all MPs are less dense than seawater and are buoyant (Andrady, 2011; Bain, 2022; Bouwmeester et al., 2015; Krause et al., 2020; Woodall et al., 2014). These positively buoyant plastic particles make fecal pellets lighter, reducing their sinking rate and, as a result, their carbon storage potential (Coppock et al., 2019; Shore et al., 2021). MPs were found to significantly reduce the density and fecal pellet sinking rate for polyethylene in the copepod *Calanus helgolandicus* (Coppock et al., 2019). MPs significantly reduced fecal pellet densities and caused a 2.25-fold decline in sinking rates in the same species of copepod (Cole et al., 2016). Shore et al. (2021) reported that contamination of polystyrene MPs slowed the pace at which fecal pellets sank by up to 1.76 times, which led to a projected 4.03-fold reduction in the volume of feces settled each day for the copepod *Acartia tonsa*. Jellyfish carcasses make a major contribution to detrital carbon and nitrogen fluxes in the ocean (Sweetman & Chapman, 2015). The consumption of MPs may prevent jellyfish carcasses from sinking and the proper functioning of the biological pump. An experimental exposure showed that as much as 46% of *Salpa (S.) fusiformis* feces retained MPs in a concentration relevant to potential future pollution scenarios (Wieczorek et al., 2019). The sinking rates of *S. fusiformis* feces were also reported to be reduced1.35- and 1.47-fold for polyethylene and polystyrene, respectively (Wieczorek et al., 2019).

The slower sinking of organic materials that results from increased buoyancy, which occurs due to the ingestion of light plastic particles, allows them to persist and float in the water column before being remineralized into inorganic substances biologically. According to recent modeling, the ingestion of MPs by organic materials may impair the carbon pump and hasten the depletion of oceanic O_2 (Kakar et al., 2023; Xu et al., 2022a, 2022b). This can be disastrous and escalate the global loss of oceanic O_2 as an increasing number of organic items no longer sink through the water column but instead become suspended, increasing microplastic pollution. If these findings were projected to the average ocean depth, fecal pellets would theoretically require approximately 7–8 weeks longer than the average time to reach the ocean floor (Galloway et al., 2017). The case of lighter polymers could be even more severe. Additionally, when organisms ingest MPs or when their permeable membranes absorb NPs, they consume less organic carbon-based matter, which also compromises carbon cycling in the aquatic ecosystem (Stoett & Vince, 2019). Although the current data may imply that slower fecal material sinking does not significantly affect the biological pump, if the rate of microplastic input continues, the biological pump's efficiency could be drastically reduced in the future. Declines in fecal material density and sinking rates due to the ingestion of MPs by animals could have a cascade effect on carbon settling and global-scale changes in carbon flux and the biological pump with increasing microplastic pollution. A significant rise in atmospheric CO_2 would be caused by limiting the operation of the biological pump in the ocean (Le Moigne, 2019).

5 Microplastics at the Water and Land Interface

5.1 Microplastics Impede the Climate Change Mitigation and Resilience of Blue Carbon Ecosystems

Vegetated coastal ecosystems, particularly mangroves, tidal marshes, seagrass, and seaweeds known as the BCE, play a crucial role in climate change mitigation and resilience through photosynthesis and carbon sequestration (Bertram et al., 2021; Macreadie et al., 2019). However, the BCE is an excellent hotspot for both macro- and microplastic deposition (Fig. 5). A substantially higher abundance of MPs is found in mangrove areas than in non-mangrove areas (Garcés-Ordóñez et al., 2019; Liu et al., 2022). The distinct root systems like pneumatophore, stilt root, and prop root provide mangrove forests with a complex structure that helps to trap plastics very effectively, resulting in increased microplastic accumulation (Duan et al., 2021; Govender et al., 2020; Martin et al., 2019; Walther & Bergmann, 2022). Many researchers also documented a significant accumulation of MPs in different seagrass (Jones et al., 2020; Seng et al., 2020; Sfriso et al., 2021), seaweeds (Feng et al., 2020; Seng et al., 2020; Sfriso et al., 2021), and salt marsh (Lloret et al., 2021; Yao et al., 2019) vegetation around the globe (Fig. 5). As a result, by attaching to the surface of these organisms and covering a substantial portion of the green regions of their bodies, MPs would block sunlight and obstruct photosynthesis. Deposited plastics can cause anoxia, resulting in suffocation, which in turn can result in pneumatophore distortion, foliage loss, limited growth, and possibly the death of the

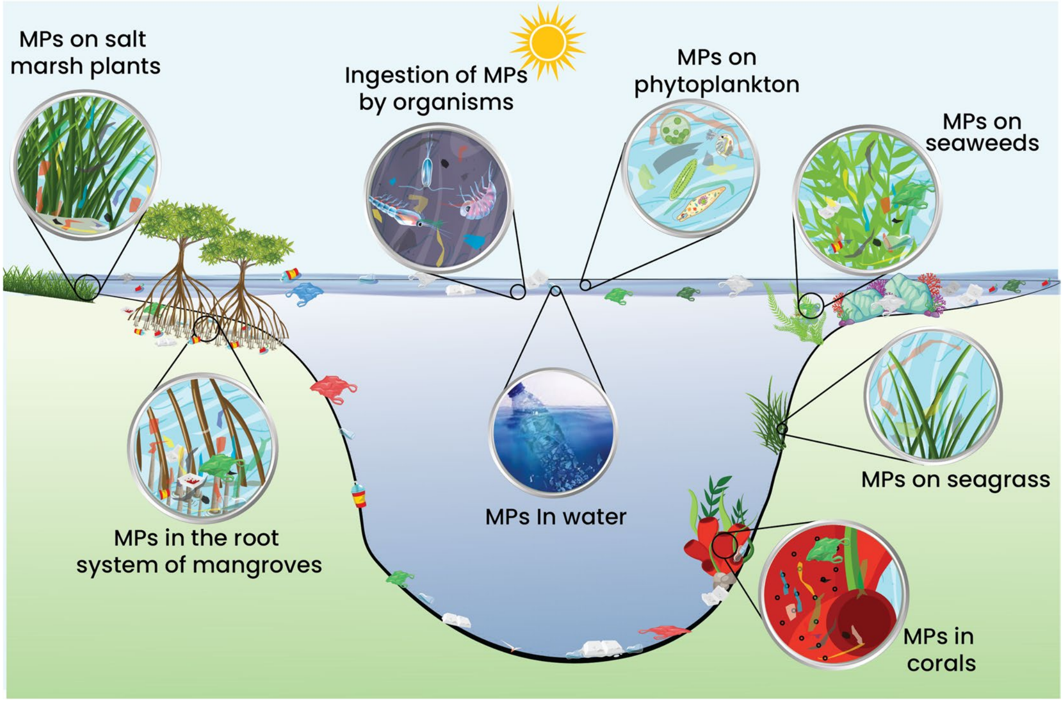

Fig. 5 MPs interfere with the growth, photosynthesis, and carbon sequestration efficiency of the Blue Carbon Ecosystems and coral symbionts in the ocean

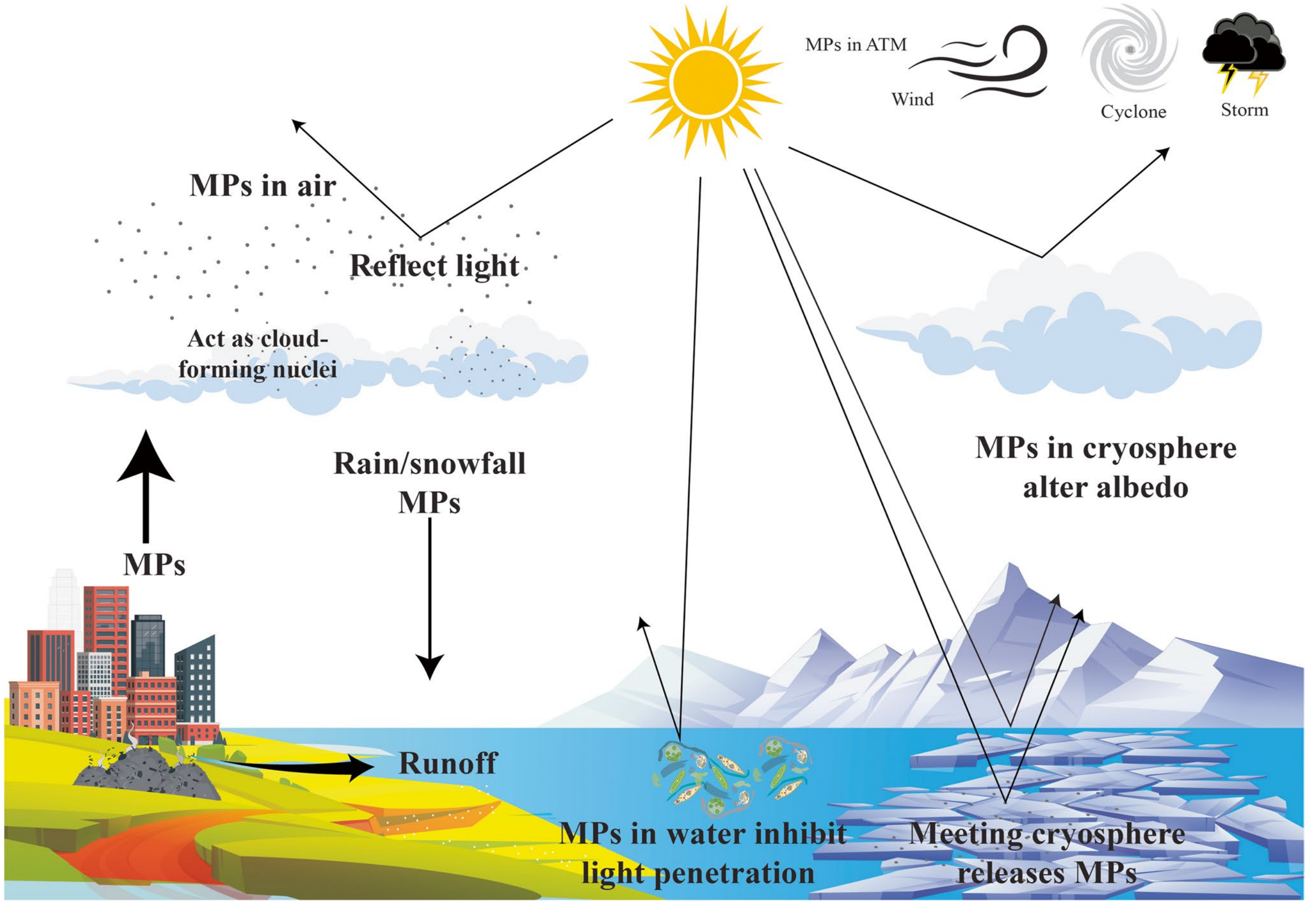

Fig. 6 The interaction of MPs in the atmosphere, hydrosphere, and cryosphere

mangroves in severe situations (Garcés-Ordóñez et al., 2019; van Bijsterveldt et al., 2021). Menicagli et al. (2022) demonstrated that PS seriously impaired the growth and photosynthesis of the seagrass *Cymodocea nodosa* by accelerating the pace of leaf loss. Mangroves are found to die at a faster rate in areas where plastics are more numerous (van Bijsterveldt et al., 2021). Such interference could impair the growth, photosynthesis, and overall carbon sequestration efficiency of the BCE.

5.2 Microplastics Affect Photosynthetic Symbionts in Corals

Not only are coral reefs among the most fascinating and diverse ecosystems on our planet, but they also help to stabilize global climate change (Graham et al., 2015). Apart from other causes, bleaching induced by climate change is currently one of the greatest dangers currently facing all coral reefs, resulting in the large-scale loss of corals (Hoegh-Guldberg et al., 2007; Okubo et al., 2020). However, the worldwide increase in plastic usage and continuous input of MPs into the coral reefs (Fig. 5) is exacerbating the pervasive global coral bleaching. Reichert et al. (2021) stated that plastics can place further stress on coral reef ecosystems, which are already burdened by climate change. MPs influence overall coral physiology, energetics, growth, and health through active intake and passive surface adhesion (Huang et al., 2021). Corals and zooxanthellae have a mutualistic relationship wherein the coral offers the algae a safe habitat, and the algae, in turn, provide the coral with important compounds required for growth. This connection is what fosters the expansion and productivity of coral reefs. MPs disrupt the commencement of the symbiotic relationship by limiting algal potency in the host, which is one of the cornerstones of rich coral reef ecosystems (Okubo et al., 2018, 2020). The photosynthesis activity of coral symbionts has also been reported to be impaired by MPs (Lanctôt et al., 2020; Su et al., 2020). Su et al. (2020) showed that PS inhibited the growth of endosymbiotic *Cladocopium goreaui*, a dinoflagellate of the *Symbiodiniaceae* family, which are key photosynthetic symbionts in coral, by altering apoptosis and metabolism, resulting in decreased photosynthesis. Additionally, MPs can prevent photosynthesis merely by covering the coral surface (Syakti et al., 2019). Another study demonstrated that polyethylene MPs reduced photosynthesis in the symbionts of *Stylophora pistillata* coral (Lanctôt et al., 2020). However, it has also been assessed that MPs, like low-density polyethylene, trigger coral bleaching and necrosis by releasing zooxanthellae in staghorn coral, *Acropora formosa* (Syakti et al., 2019). A recent laboratory experiment demonstrated that the breakdown of plastics in the sea drives ocean acidification (Romera-Castillo et al., 2023). Coral bleaching by the co-occurrence of climate change–induced ocean acidification and aggravation of MPs would be disastrous for coral reef ecosystems, as it was observed that bleached corals incorporated more MPs than did healthy corals (Okubo et al., 2020).

6 Microplastics in Soil: Microplastics Induce Greenhouse Gas Emissions from the Soil

Soil serves as a major repository for MPs (Cramer et al., 2022; Rillig, 2012) (Supplementary Information Table 3). The presence of MPs in soils harms their structure and physical properties, including soil aggregate water stability, bulk density, pneumatic conductivity, rhizosphere function, and the development of new aggregates (Ingraffia et al., 2022; Mbachu et al., 2021; Rillig et al., 2021). MPs in soils affect the makeup of the microbial population and provide a special habitat for microbes, which may have an impact on the ecological processes that occur in soil ecosystems (Gao et al., 2021a, 2021b; Huang et al., 2019; Seeley et al., 2020). MPs also affect the activity and functional diversity of different enzymes in soils (Qin et al., 2023; Xu et al., 2020; Yu et al., 2021). Yang et al. (2018) reported that glyphosate decay and microbial activities, particularly respiration, significantly changed with the addition of MPs in soils. MPs impact sedimentary microbial ecosystems and global biogeochemical cycling systems (Seeley et al., 2020). According to recent studies, soil MPs may impact carbon cycling in soil and the ability of soils to store carbon, thus affecting how much nitrous oxide (N_2O) and CO_2 are released into the atmosphere as greenhouse gases (Nunez et al., 2022; Qin et al., 2023; Rillig et al., 2021; Wang et al., 2022a, 2022b; Yu et al., 2021). MPs have been shown to increase the emission of CO_2, N_2O, and other GHG from the soil through changing physical and microbiological properties, ultimately leading to global climate change (Chen et al., 2022; Gao et al., 2021a, 2021b; Rillig et al., 2021; Wang et al., 2022a, 2022b). The coexistence of PE and hydrochar (a carbon-rich material) in soil increased methanogen gene (mcrA) activity, leading to higher CH_4 emissions by 83.5% and intensity of GHG by 36.0% (Han et al., 2022). It has been observed that the coexistence of PE-MPs and biochar boosted the emission of N_2O up to 37.5% in agricultural soil, demonstrating how MPs induce the emission of GHG (Li et al., 2022a, 2022b). Global warming can be greatly exacerbated by the release of CO_2 and N_2O from the soil (Gao et al., 2022). Furthermore, MPs have repercussions on the plant-soil system by altering soil biophysical characteristics, leading to an impact on the plant community composition as well as plant health, primary production, and overall performance (De Souza Machado et al., 2019; Nayab et al., 2022; Rillig et al., 2019). This could eventually contribute to climate change by upsetting the global oxygen and carbon cycles.

7 Microplastics in the Air

MPs have a global distribution, affecting seas, lakes, rivers, and the terrestrial ecosystem. Recently, however, like other elements of the environmental matrix, MPs seemed to be present in the atmosphere of the planet as well (Supplementary Information Table 4). Due to their small size and low material density, MPs can be readily resuspended from the land into the air and carried great distances by atmospheric circulation (Ding et al., 2022; Liu et al., 2019). The prevalence of MPs in the atmosphere could affect weather, including rainfall, wind, and the global climate.

7.1 Microplastics Contribute to Cloud Formation

In the atmosphere, the condensation of water vapor surrounding any microscopic particles floating in the air transforms them into liquid droplets or ice crystals. The accumulation of a large number of such droplets or ice crystals eventually forms clouds. Usually, tiny airborne particles such as dust and salt crystals provide surfaces for water vapor to condense into liquid droplets as cloud-condensing nuclei. MPs are ubiquitous in the atmosphere and prevalent in both outdoor and indoor air, which results in atmospheric deposition (Wright et al., 2020). MPs and NPs present in the atmosphere, similar to dust and salt particles, can act as nuclei in cloud formation (Aeschlimann et al., 2022; Ganguly & Ariya, 2019) (Fig. 6). When MPs come into contact with organic molecules, they are reported to operate as hygroscopic nuclei, making them more significant for cloud formation (Abbasi, 2021; dos Santos Galvão et al., 2022). Wang et al. (2023) detected MPs with hydrophilic groups, like hydroxyl and/or carbonyl groups, at high altitudes, suggesting that they may have served as cloud condensation nuclei and, therefore, might be affecting the climate. Thus, there may be unusual rainfall events during the offseason or an alteration of monsoon onset, particularly in areas with a high microplastic load in the air prevailing together with other atmospheric conditions favorable for cloud formation. MPs are already regarded as persistent air pollutants, and their abundance will continue to rise unless significant changes are made in the production and disposal of plastic (Revell et al., 2021; Zhang et al., 2020). As a result, release of more MPs in the atmosphere could have a substantial influence on cloud formation, contributing to climate change (Ganguly & Ariya, 2019). Furthermore, the MPs in a cloud could be washed out by rainfall (Fig. 6), enhancing the movement of MPs in the atmosphere and in pristine places far from plastic pollution sources (Abbasi, 2021; Li et al., 2022a, 2022b; Wright et al., 2020; Xia et al., 2020). Wang et al. (2023) reported the presence of MPs in high-altitude cloud water sampled at the mountain summit at 1300–3776 m altitude.

7.2 Microplastics Inhibit Atmospheric Cooling

Sea spray aerosols (SSA) are tiny particulate materials emitted directly from the ocean by bubbles bursting into the air via the ocean–atmosphere interface (Liu et al., 2021; Rafla, 2022; Xu et al., 2022a, 2022b). They are the most important particulate materials emitted by the ocean, dominating the aerosol mass in the marine boundary layer and accounting for a significant portion of aerosols in the atmosphere (Liu et al., 2021; Xu et al., 2022a, 2022b). It is evidenced that atmospheric aerosols influence the climate by scattering incoming short-wave radiation from the sun (Myhre et al., 2013; Schiffer et al., 2018). SSA materials, like any other atmospheric aerosols, scatter incoming solar radiation, cooling the atmosphere by increasing total reflected energy from the Earth (Myhre et al., 2013; Rafla, 2022; Revell et al., 2021). Weather and climate are significantly influenced by the interchange of vapor and heat between the surface and atmosphere of the Earth (Fairall et al., 1990). Sea spray evaporation influences the latent and sensible heat fluxes via the ocean–atmosphere interface (Rastigejev & Suslov, 2019). Current simulations demonstrate that SSA considerably boosts the sensible heat flux at the ocean surface, and the heat carried by SSA, particularly the latent heat, is the crucial factor in the ocean–atmosphere heat balance (Andreas, 1992; Richter & Sullivan, 2014). SSA also acts as cloud formation nuclei, playing an important role in marine cloud formation. Given that the ocean accounts for three quarters of the Earth's surface, SSA have the potential to significantly affect both the development of clouds and the balance of atmospheric radiation, which are critical for maintaining the global heat budget (Rafla, 2022; Xu et al., 2022a, 2022b). However, MPs affect the formation of SSA from the sea, and as a result, this cenotaph issue of increased plastic litter in the ocean may inhibit the cooling of the atmosphere and weaken the influence of SSA over the Earth's climate (Rafla, 2022). Furthermore, recent discoveries of MPs in the atmosphere in urban, suburban, and even isolated locations far from the sources of MPs have led to the perception that they are as pervasive in the atmosphere as they are in the ocean (Revell et al., 2021; Zhang et al., 2020). Increased airborne MPs, especially those that are deeply colored or darker than light, can hamper the cooling process in the atmosphere by absorbing incoming solar energy. When MPs and NPs are present at sufficient levels in the atmosphere, they can modify cloud albedo, precipitation, and longevity, all of which affect the Earth's temperature and radiation balance (Aeschlimann et al., 2022).

8 Microplastics in the Total Environment (Water, Soil, and Air)

8.1 Extreme Climate Change Events Facilitate the Spread and Prevalence of Microplastics in the Environment

Most plastic materials are used on land, and cities are the main hotspots of plastic pollution (Hale et al., 2020; Jia et al., 2022). Significant portions of the materials are not recycled and are discarded as debris every day all over the globe. Such unmanaged plastic debris exposed in the air becomes fragile, generating MPs through UV radiation–induced photo-oxidative and thermo-oxidative degradation (Andrady, 2011). MPs that are introduced to the environment move to a wide range of areas in response to external influences such as wind and ocean currents (Gong & Xie, 2020). Meteorological factors, notably, rain and wind, influence the deposition, particle size, and form of MPs in a specific area (Jia et al., 2022). The runoff after rainfall, storms, and floods ultimately carries loose plastic wastes into the ocean via terrestrial systems and river networks (Fig. 6). Around 80% of the plastics in the oceans across the world are postulated to have been transported through this pathway (Ockelford et al., 2020). Weather variables and climatic conditions influence the transportation of plastic wastes from land-based sources to river systems and oceans (Campanale et al., 2020). Global warming contributes to inducing increasingly frequent and severe extreme weather events occurring across the entire planet (WMO, 2022). It is becoming increasingly evident that extreme events, such as storms and floods, are sweeping away terrestrial MPs into the oceans via freshwater systems as a faster conduit for these wastes that we discard in our daily lives (Fig. 6). Each rainfall event contributes to increasing the microplastic concentration in aquatic systems; therefore, the more rainfall, the stronger the surface runoff on land and the greater the amount of plastic debris transported (Xia et al., 2020). Hitchcock and Mitrovic (2019) showed a significant positive relationship between microplastic abundance and rainfall events in different water bodies. A considerable number of MPs are present in the Earth's atmosphere (Gasperi et al., 2018; Klein & Fischer, 2019); therefore, apart from being carried through runoff, MPs can also be transported directly into water bodies by adhering to raindrops during rainfall (Abbasi, 2021; Xia et al., 2020) (Fig. 6).

Extreme events such as hurricanes and cyclones distribute MPs to pristine areas, and the rise of sea level will remove more trash from beaches through tidal flushing (Ford et al., 2022; Stoett & Vince, 2019). The abundance of macro-debris and MPs was observed to surge dramatically after a cyclone, being 40-fold higher during the storm than before (Hitchcock, 2020; Lo et al., 2020). Cho et al. (2023) found MPs in stormwater runoff from industrial and residential regions spanning from 68 to 568 n/L and 54 to 639 n/L, respectively, and concluded that such runoff is a primary route for the passage of terrestrial MPs to water bodies. Almost similar findings have also been reported for the case of flooding, after which there was a 14-fold increase in MPs (Gündoğdu et al., 2018). Water turbulence caused by these events stirred MPs that were retired at the bottom, leading to their re-suspension and further dispersion. Sun et al. (2023) reported a significant relationship between storms and microplastic abundance. Stronger waves, such as those produced during storms, also retrieve MPs buried in the coastal sediments, which is a significant reserve for MPs (Xu et al., 2023). This became more evident from the report of Sun et al. (2023), who noticed an alteration in the properties of MPs throughout a storm, with an upsurge of small-sized MPs in severe storm parameters. The storm facilitates the rise of MPs on the surface, which will aggravate the negative impacts (Xia et al., 2020). Strong wind and turbulence from extreme events produce enormous waves on the sea surface. When waves break, air bubbles burst, expelling salt crystals into the atmosphere along with salt, where they are then transported by the wind. Many researchers have demonstrated that plastic particles, probably in the nano-size range, are dispersing from the ocean in this bursting bubble or sea spray-forming process (Allen et al., 2020; Bain, 2022; dos Santos Galvão et al., 2022; Shiu et al., 2022). Lehmann et al. (2021) reported that spray contained microplastic particles in laboratory experiments. Using a global model based on bubble scavenging and bursting physics, local wind and sea state experts estimated that the ocean emits between 0.02 and 7.4 million metric tons of plastic per year, with a best estimation of 0.1 (Shaw, 2023). Droplets formed from the impact of raindrops on water surfaces also transfer MPs through the water–air interface from the hydrosphere to the atmosphere, similar to bursting bubbles (Lehmann et al., 2021). MPs have been found in air masses over water bodies around the globe (Ferrero et al., 2022; Habibi et al., 2022). Indeed, evidence has recently been presented confirming that an interaction exists between atmospheric transport and emissions from the sea and that MPs once deposited in the sea can be emitted again into the air (Ferrero et al., 2022). Thus, once plastics, whether as primary or secondary MPs and regardless of origin, enter the environment, they will be dispersed across different parts of the world. A recent study that discovered MPs in the Antarctic air attests to this fact (Marina-Montes et al., 2022).

Additionally, typhoon-induced turbulence, for example, has also been reported to redistribute MPs in coastal areas and reform plastisphere communities with potential enrichment of nitrogen fixers, such as Bradyrhizobiaceae, which may impair the nitrogen cycle and increase the possibility of eutrophication in the coastal environment (Chen et al., 2021a, 2021b). Global warming increases the rate of evaporation in water bodies, which raises water salinity and density. This rise in water density makes MPs more likely to remain for a longer time in aquatic bodies (Kakar et al., 2023). In recent decades, as the ocean surface has heated as a result of global warming, tropical cyclones (TC) have become more frequent and intense, coupled with precipitation and cascade effects (Chen et al., 2021a, 2021b; Knutson et al., 2019; Knutson et al., 2021). Moreover, this trend is projected to be more severe, with a significantly elevated risk of extreme weather events like TC, typhoon precipitation, floods, and higher storm inundation levels in the future warming world (Chen et al., 2020a, 2020b; Knutson et al., 2019; Li et al., 2022a, 2022b; Zhu et al., 2021). Intensified and frequent extreme weather occurrences caused by global warming will drive the recirculation of these MPs between marine and terrestrial environments (Li et al., 2022a, 2022b). This would promote the redistribution of MPs as well as their impacts in remote, pristine areas far from pollution sources, which would exacerbate the wide-reaching impacts of plastic pollution.

9 The Co-occurrence of Both Microplastics and Climate Change Crises Could be Disastrous

Climate change and plastic pollution crises are currently threatening our globe, and if they both strike simultaneously in aquatic environments, the results might be disastrous (Ford et al., 2022). The melting of icebergs, ice sheets, permafrost, and glaciers in the cryosphere worldwide is one of the most obvious results of a rise in global temperatures. MPs are trapped within sea ice during its production and will be freed whenever it melts (Geilfus et al., 2019; Hoffmann et al., 2020). Future permafrost thaws and breakdowns will be accelerated by climate change, which will affect global microplastic cycling (Chen et al., 2021a, 2021b). Thus, large ice-covered portions of the planet may become subject to new plastic pollution due to the opening of ice-free areas and the recovery of ice-bound MPs as a result of escalating global warming (Fig. 6), which would place an additional burden on the already vulnerable ecosystems (Botterell et al., 2022). Significant amounts of microplastic particles darker than the cryosphere could also alter the albedo, increasing solar absorption and, as a result, enhancing melting and releasing additional plastics in nature (Bergmann et al., 2015; Evangeliou et al., 2020; Geilfus et al., 2019; Zhang et al., 2022). The increase in the number of MPs discharged into the water from melting in the cryosphere will, like other sources of pollution (Fig. 6), affect the ecosystem and climate in a loop.

MPs interact with several biotic and abiotic factors and can severely affect population health and well-being when paired with other hazards (Seeley et al., 2023). The combination of warming and microplastic contamination hindered the growth, body size, chlorophyll-a content, and photosynthesis of the phytoplankton *Chaetoceros gracilis* (Hou et al., 2023). Bertucci and Bellas (2021) reported that the early growth and development of the sea urchin *Paracentrotus (P.) lividus* are affected by the simultaneous effects of MPs and warming. In the case of potential future scenarios of global climate change, the ability of *P. lividus* to survive in the ecosystem is seriously challenged due to the alteration of water chemistry caused by both ocean acidification and microplastic pollution (Bertucci et al., 2022). The combined effect of MPs and ocean acidification severely impairs the ability of thick-shell mussels, *Mytilus coruscus*, to digest their food, along with affecting oxidative reactions (Wang et al., 2020). The co-occurrence of both MPs and warming suppressed the metabolic rates and physiology of *Gammarus pulex*, a model benthic detritivore in European running waters (Kratina et al., 2019). The simultaneous effects of microplastic pollution and ocean acidification increase the vulnerability of bivalves to diseases and dislodgment, endangering their lives (Huang et al., 2022). Firmino et al. (2022) also found that both MPs and climate change significantly affected the consumption and survival of an Amazon stream shredder, which could have an impact on ecosystem functioning in addition to affecting the population level.

10 Research and Policy Implications

The challenges posed by both plastic pollution and climate change have become important public and policy issues (Ford et al., 2022). While some scientists work on plastic pollution and others on climate change, both problems are interrelated, have interdependent factors, and have important ethical and policy implications (Ford et al., 2022; Stoett & Vince, 2019). The complexity of these global issues impacts human health and well-being, ecosystems, and the economy. In this context, it is urgent to take action and implement effective strategies for confronting microplastic pollution. It is important to emphasize source control, increased use of biodegradable materials, and improved remediation or clean-up efficiency, along with the reuse, recycling, and recovery of plastics. We recommend the following key points for reducing microplastic pollution:

- Control of MPs in sources through enforcement laws and regulations at the national and international levels
- Reduce, reuse, and avoid single use plastics
- Promoting reusable goods
- Development and use of eco-friendly or biodegradable materials
- Following improved waste management system
- Development of efficient remediation or clean-up technology
- Raising mass awareness on the issue

However, addressing both the MPs and climate change crises simultaneously would be more effective and sustainable than handling one challenge in isolation. For instance, MPs contribute to climate change in various ways, and climate change also triggers the redistribution of MPs and their spread to previously untouched areas. Given the interconnectivity of these challenges, it is essential to approach them together rather than addressing them separately and dividing efforts. An integrated policy and management approach that recognizes the links between pollution and climate change and takes a holistic view of their causes, effects, and solutions is crucial to effectively addressing these issues. This will require collaboration and coordination across sectors, disciplines, and levels of government, as well as the development of policies and programs that tackle both pollution and climate change simultaneously. An integrated policy approach can lead to more comprehensive and cost-effective solutions to these challenges. To achieve this integrated approach, the following key elements are important:

- Holistic vision: A comprehensive strategy that considers the interlinked nature of the two challenges and addresses them in an integrated manner.
- Cross-sectoral collaboration: Collaboration between different sectors, such as environment, energy, agriculture, transportation, and waste management, is necessary to find integrated solutions.
- Incentives and disincentives: Policies that incentivize environmentally friendly behavior and disincentivize harmful practices can be effective in promoting sustainability.
- Monitoring and evaluation: Regular monitoring and evaluation of the impact of policies and measures are crucial to determining their effectiveness and adjusting the strategy as needed.

This research points to crucial implications, particularly underscoring the pressing need to recognize microplastic pollution as more than just an environmental threat. This study improves our perception on the effects of MPs, which extend beyond ecological degradation and include a substantial impact on climate change. Importantly, both plastic pollution and climate change are transboundary issues. Thus, strong global and regional agreements and treaties can also play a role in minimizing and eliminating plastic pollution by encouraging cooperation among governments, producers, scientists, and the public through incentives. Additionally, this comprehensive review suggests that the scientific community needs to collaborate and integrate its research efforts on plastic pollution and climate change. This can be done by promoting interdisciplinary research teams and exchanging knowledge and data across different scientific fields. It is also necessary to engage all relevant stakeholders, such as policymakers and industry, to ensure that research findings are translated into practical and effective solutions addressing the interrelated nature of plastic pollution and climate change. We highlight that promoting public awareness and education on these issues can also help foster greater support for integrated approaches to tackle the complex global challenges and their wide-ranging implications. The information in the article would be helpful for upcoming studies in the fields of MPs, climate change, and allied sciences. Microplastic pollution, as demonstrated here, should be seen as a crucial wake-up call that demands our attention to its deep and serious implications. We hope this effort will provide momentum for the scientific community and decision-makers to eventually devise effective ways to address the plastic–climate conundrum.

11 Conclusion

We highlighted the role that MPs play in contributing to global warming throughout their life cycle, from production to disposal, as well as their stay in nature. Although the extent to which MPs contribute to global warming is not entirely understood yet, it is clear that they certainly contribute to climate change crises. The extraction, transportation, refinement, and manufacture of plastic, along with waste disposal and degradation, result in different greenhouse gas emissions. In nature, MPs interact with different components of the hydrosphere, atmosphere, lithosphere, and biosphere, leading to increased greenhouse gas emissions and impairing various climate processes. In the hydrosphere, MPs hinder the ocean's ability to mitigate the effects of climate change by affecting the growth and photosynthesis of blue carbon ecosystems, reducing their ability to generate oxygen, store carbon, and provide other ecosystem services and climate resilience. MPs also reduce the oxygen content in water and induce deoxygenation in the ocean. They impede the carbon sequestration and climate resilience potential of the blue carbon ecosystem. MPs in the lithosphere, particularly in soil, alter the physical properties, leading to an impact on the primary production and overall performance of the plants, upsetting the global oxygen and carbon cycles. MPs in soils also affect the makeup and activity of the microbial population, inducing the emission of different greenhouse gases. Climate change has induced extreme events that spread and redistributed MPs in the environment, exacerbating the problem. The challenges of plastic pollution and climate change are intrinsically related, although they are treated separately. These global challenges are occurring together with additional stressors that jeopardize the resilience of different ecosystems. Further research is essential to explore the interplay between plastic pollution and climate change. This requires collaboration between the major stakeholders, such as policymakers, researchers, and the public. We emphasize an integrated and holistic approach to finding effective and sustainable measures for tackling the crises together.

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Declarations

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