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Microplastics, the ubiquitous pollutant accompanying Climate Change: A bibliometric analysis of the context

Microplásticos, el contaminante ubicuo acompañante del Cambio Climático: Un análisis bibliométrico del contexto

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Resumen

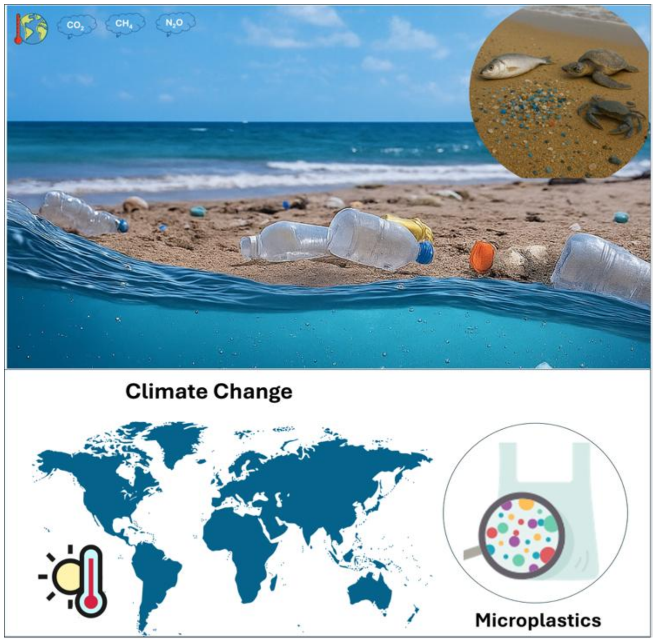
La contaminación de los ecosistemas por fragmentos plásticos menores a 5 mm de longitud (microplásticos, MPs), y el Cambio Climático (CC), amenazan la salud de los ecosistemas terrestres y acuáticos, la biodiversidad y representan una amenaza indirecta y creciente para la salud humana. Debido a que ambos fenómenos ocurren de forma paralela a escala global, es interesante indagar si se influyen mutuamente. Por lo tanto, en este estudio se revisó el estado del arte del efecto de los MPs sobre el CC y se discutieron los posibles mecanismos que llevan a los MPs a favorecer el CC. Para tal fin, se realizó un análisis bibliométrico con publicaciones de la base de datos Scopus, y se complementa la discusión con información de artículos relevantes sobre la relación entre los MPs y el CC. Los resultados evidenciaron que se trata de un campo de conocimiento en desarrollo, enmarcado en 5 a 6 clusters de áreas de estudio: sustentabilidad, cambio climático y vida marina, efectos sobre organismos, componentes transportados por MPs, métodos de caracterización química de MPs, y efectos sobre la salud humana. Además, la mayoría de los análisis de la interacción MPs-CC se basan en supuestos teóricos sustentados por evidencia empírica limitada, generalmente centrada en un sólo componente. No obstante, los pocos estudios empíricos donde se relacionan ambos eventos demuestran que la contaminación por MPs puede intensificar el CC al inducir la emisión de Gases de Efecto Invernadero (GEI), mediante alteraciones en los ciclos biogeoquímicos del agua y los sedimentos en los ecosistemas acuáticos y terrestres. Estos hallazgos resaltan la urgencia de realizar investigaciones experimentales y de campo, que permitan cuantificar y esclarecer los mecanismos subyacentes de la interacción bidireccional de los MPs y el CC al medio ambiente

***Palabras clave*:** Contaminación ambiental, Ciclos biogeoquímicos, análisis de redes, Gases de Efecto Invernadero, Ecosistemas acuáticos y terrestres.

Abstract

The contamination of ecosystems by plastic fragments smaller than 5 mm in length (microplastics, MPs) and Climate Change (CC) threaten the health of terrestrial and aquatic ecosystems, biodiversity, and they represent an indirect and growing threat to human health. Because both phenomena occur simultaneously on a global scale, it is interesting to investigate whether they influence each other. Therefore, this study reviewed the state-of-the-art on the effect of MPs on CC and discussed the possible mechanisms that lead MPs to promote CC. To this end, a bibliometric analysis was conducted with publications from the Scopus database, and the discussion was complemented with information from relevant articles on the relationship between MPs and CC. The results showed that this is a developing field of knowledge, framed in five to six clusters of study areas: sustainability, climate change and marine life, effects on organisms, components transported by MPs, methods for chemical characterization of MPs, and effects on human health. Moreover, most analyses of MPs-CC interactions are based on theoretical assumptions supported by limited empirical evidence, generally focusing on a single component. However, the few empirical studies linking the two events demonstrate that MPs pollution can intensify CC by inducing greenhouse gas (GHG) emissions through alterations in the biogeochemical cycles of water and sediments in aquatic and terrestrial ecosystems. These findings highlight the urgent need for experimental and field research to quantify and clarify the underlying mechanisms of the bidirectional interaction of MPs and CC with the environment.

***Keywords*:** Environmental pollution, Biogeochemical cycles, Network analysis, Greenhouse gases, Aquatic and terrestrial ecosystems.



1. Introduction

The increase in global plastic consumption, such as through fast fashion and frequent clothing changes using single-use plastics, or consuming bottled water, are everyday practices actions that promote the production and dispersion of plastic particles smaller than 5 mm, known as microplastics (MPs). These particles, including nanoplastics (smaller than 1 µm), have become ubiquitous, being found in virtually all ecosystems and organisms studied (Fig. 1). Furthermore, it has been suggested that they could synergistically contribute to the increase in global temperature [1].

MPs are considered emerging and persistent pollutants, globally widespread due to their long-term presence in the environment. They have been found in aquatic and terrestrial ecosystems, in the air, and even in human blood, human skeletal tissue, and breast milk [2], [3], [4], [5]. In our laboratory, MP particles were analyzed and detected in rainwater, lagoon water in a Colombian Neotropical alpine ecosystem, rivers, and bottled water, demonstrating their widespread dispersion even in environments with low human intervention. Furthermore, it has been proved, both naturally and experimentally, that MPs can transport pathogenic bacteria attached to their surface [6].

In addition to the textile industry, agriculture is an important source of MPs due to the "fertilization" of soils with activated solids from wastewater treatment plants, the use of protective films and fruit transport, the construction of greenhouses, and irrigation systems where single-use plastic materials are used [reviewed in 1], [7], [8]. These contaminants affect soil quality and plant physiology through mechanical and cytotoxic damage and bioaccumulation in leaves, roots, and stems [9], [10]. Consequently, MPs affect agricultural production and, in general, terrestrial and aquatic primary productivity [11], [12], [13]. The impact of MPs on soil fertility is related to aeration, moisture retention, and changes in microbial communities responsible for nutrient recycling or biogeochemical cycles [14], [15]. This is where the relationship between MP contamination and its effect on Climate Change (CC) could lie, in the loss of the capacity of primary producers to capture CO_2, and in the increase in soil respiration [16], [17], [18].

Climate change refers to anomalous and persistent variations in climate on a planetary scale that affect the entire Earth system. These variations are manifested in the accelerated increase in global temperature since the beginning of the pre-industrial period (1850-1900), a phenomenon closely related to the rise in atmospheric concentrations of greenhouse gases (GHGs). Among these, the most significant due to their Global Warming Potential (GWP) are carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) [19].

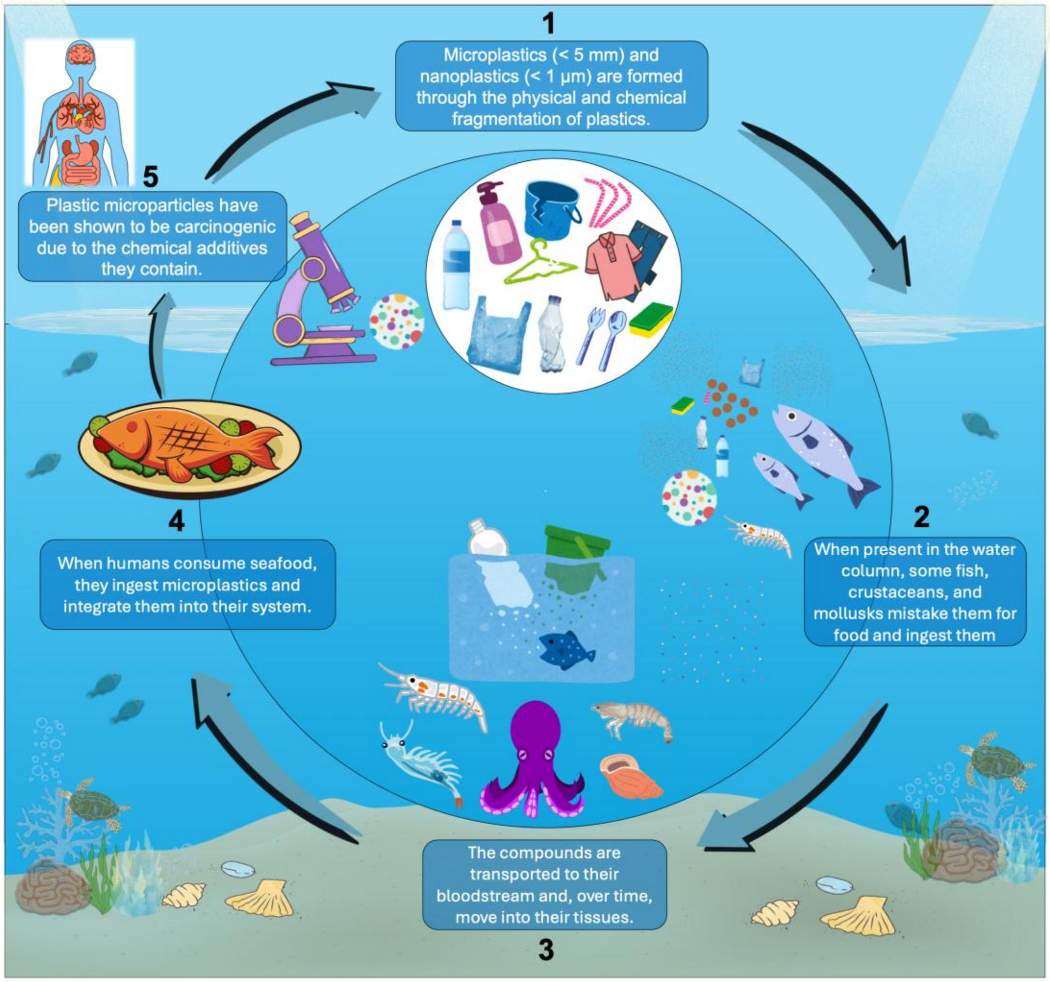


Figure 1. Microplastic cycle in marine ecosystems and its impact on human health. **(1)** Microplastics are generated by the physical and chemical fragmentation of plastic products, forming particles smaller than 5 mm and nanoplastics smaller than 1 µm. **(2)** These particles remain suspended in the water column, where they are ingested by fish and other marine organisms that mistake them for food. **(3)** Microplastics and their compounds are distributed in the bloodstream and tissues of these organisms. **(4)** When humans consume seafood, they incorporate these contaminants into their bodies. **(5)** Plastic microparticles may contain chemical additives with carcinogenic effects and other risks to human health [20, 21, 22]. Illustration: N. Carabantes, LP. Suescún-Bolívar and A. Santamaría-Miranda.

Globally, all humans contribute to carbon (C) emissions into the atmosphere. On average, a person generates approximately 1.8 metric tons of CO_2 equivalent (tCO_2e) per year, translating into 126 tCO_2e over an average lifespan of 70 years [23]. According to estimates based on the "human climate niche", this level of emissions can expose more than one person to unprecedented global heat in the future. However, this contribution could be greater if you are a US citizen or a Qatari, who produces more than double or 10 times more tC than the global average, respectively [23].
The unprecedented temperature increase recorded in recent months has been driven by the rise in Ocean Heat Content (OHC). This heat "trapped" by ocean water masses is the thermal energy stored in a volume of ocean water, from the water surface to the depth where the isotherm (temperature at a certain depth that remains close to constant) of 26 °C is located. As reported by Brian McNoldy, so far in 2024 (https://bmcnoldy.earth.miami.edu/tropics/ohc/). The Tropical Atlantic and Caribbean Sea have exceeded historical OHC averages (from 2013 to 2023), causing severe heat stress on sensitive marine animals and ecosystems such as coral reefs in the Tropical Atlantic, which are literally "dying of heat." Added to this is the melting and loss of Arctic ice regeneration, which could slow the transport of water in the Atlantic Meridional Overturning Circulation (AMOC), triggering catastrophic events like those recorded during the last interglacial period [24], with heat waves in the tropics and extreme cooling at the poles. Disruption of the AMOC would compromise its role in global climate regulation, affecting the exchange of heat, gases, and nutrients between the ocean water in the tropics and the poles. This event would also impact upwelling systems and marine productivity (e.g., large fisheries). Overall, this is one of the most critical climate change scenarios in human history.

Because MPs' pollution and climate change currently coexist, this study conducted a bibliometric analysis of their

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potential interactions. The objective was to determine the links between both phenomena and obtain bibliographical recognition of the progress in this area of knowledge. It was found that this relationship represents an emerging field of research worth addressing, with growing evidence indicating that MPs contribute to climate change by altering biogeochemical cycles that directly affect the balance of production of the most important GHGs. Furthermore, both phenomena exert negative synergistic effects on the physiology of organisms and accelerate environmental deterioration.

2. Methods

To assess the current state of research on the interaction MPs with CC), a search was conducted in the Scopus database using the equation: ALL ("global warming" OR "climate change") AND "microplastic." The Scopus database was selected due to its broad multidisciplinary coverage, encompassing indexed journals across natural sciences, engineering, social sciences, arts, and humanities. This makes it more suitable for the scope of this review, which requires an interdisciplinary perspective.

Metadata from all publications found were extracted into a .csv file format and analyzed using VOSviewer (version 1.6.20) employing co-occurrence analysis with author keywords, using two iteration parameters: 10 and 50. In addition, key articles addressing the interaction between both global phenomena were identified [11], [12], [18], [13], [25], which were integrated to enrich the contextual analysis of this study.

3. Results and Discussion

3.1 Bibliometric analysis of the study area and keyword co-correlation

The search returned 7,455 published documents, primarily scientific papers, reviews, and books. Publications on the relationship between MPs and CC have been increasing exponentially over time (Fig. 2), starting with 8 publications in 2014 and reaching 1964 documents so far in 2024 (September 19, 2024). These data show that this is a developing area that warrants attention. In the list of a total of 16,801 author keywords, the number of words that reached iteration levels 10 and 50 was 453 and 51, respectively (Fig. 2). In the generated With a threshold of 10 (Fig. 3A), six main clusters were identified, representing strongly related subject areas. These clusters show the areas of knowledge where information is being generated around the main words used in the search. For example, the relationship between Climate Change (CC) and marine life, plastic pollutants, and MPs is shown in red. It also shows how it relates to the sustainability node (yellow-green), to changes in aquatic ecosystems and the Arctic (light blue), to stress on organisms (dark blue), and to the interaction of MPs with components that could be transported by adsorption, such as heavy metals and microorganisms (dark green). MPs are mutually related to CC and the other groups.

network, each node shows a keyword that reached the minimum threshold, the larger the node, the greater the frequency of occurrence of the word. The color and the iteration line indicate the strength of the relationship between one node and another, that is, the number of times these words are mentioned together. Therefore, if the same color is connected to the lines, the frequency of occurrence of these words together is greater than that of another word with a different color.

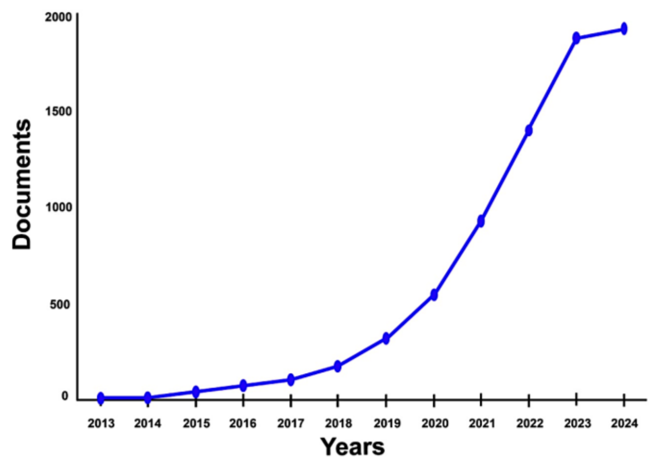

Figure 2. Publications on MPs and CC. The number of publications obtained using the search equation ALL ("global warming" OR "climate change") AND "microplastic" in the Scopus database is shown. The number of documents has increased exponentially since 2018. Documents = number of publications. Year = time range measured annually from 2013 to September 2024.

By increasing the co-occurrence threshold to 50 (Fig. 3B), the map highlights the interrelationship between studies on MP pollution and CC. This visualization highlights the growing focus on analyzing the synergistic effects of both global phenomena (MPs on CC) and the joint effect of these events on ecosystems and living organisms, reflecting the current state of scientific research in this emerging area.

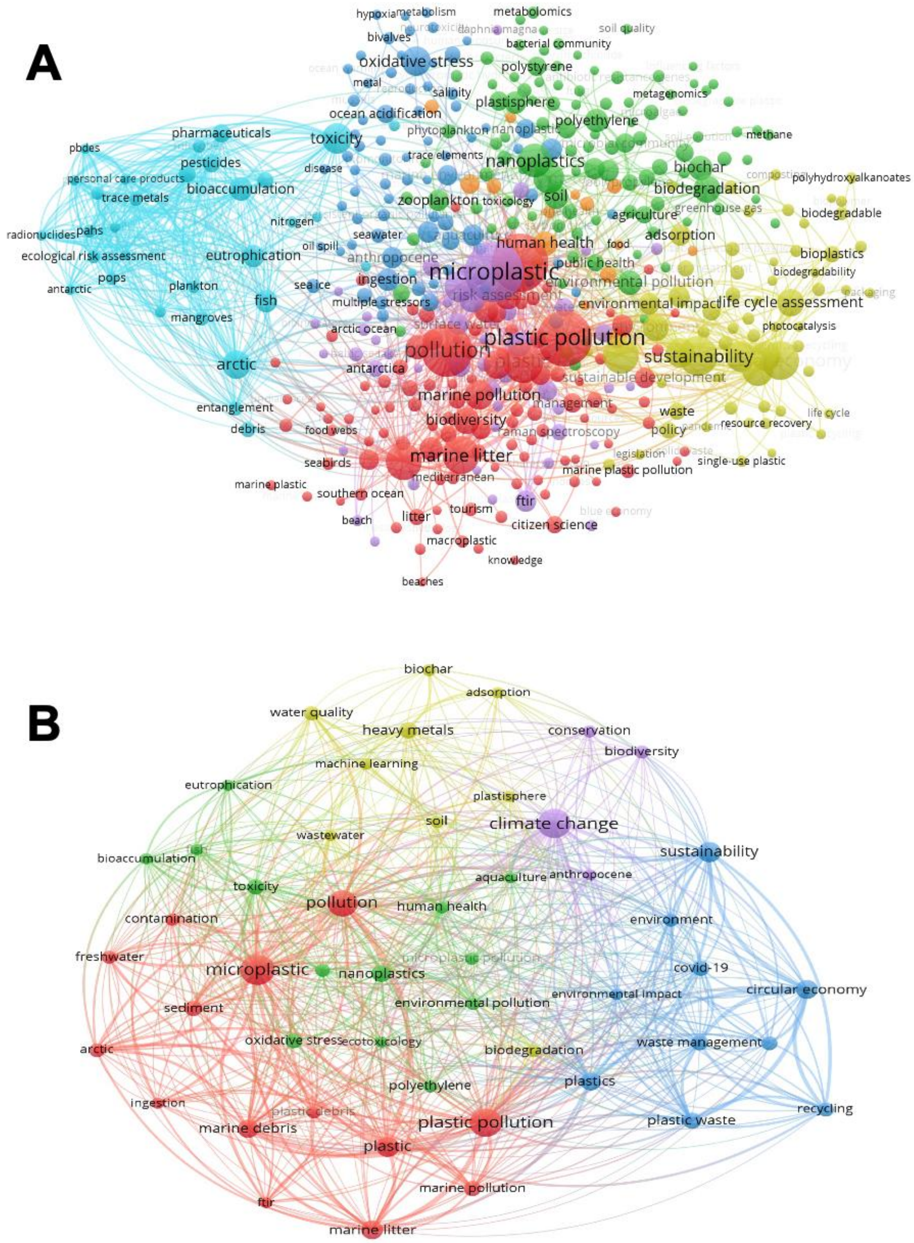

Figure 3. Co-occurrence analysis of author keywords in publications on microplastics and climate change. **A.** Network created with 10 iterations, showing 6 keyword groups. **B.** Diagram created with 50 iterations, clearly shows the relationship between MPs and CC, grouped into 5 groups. See the text for more details. Maps created using VOSviewer software.

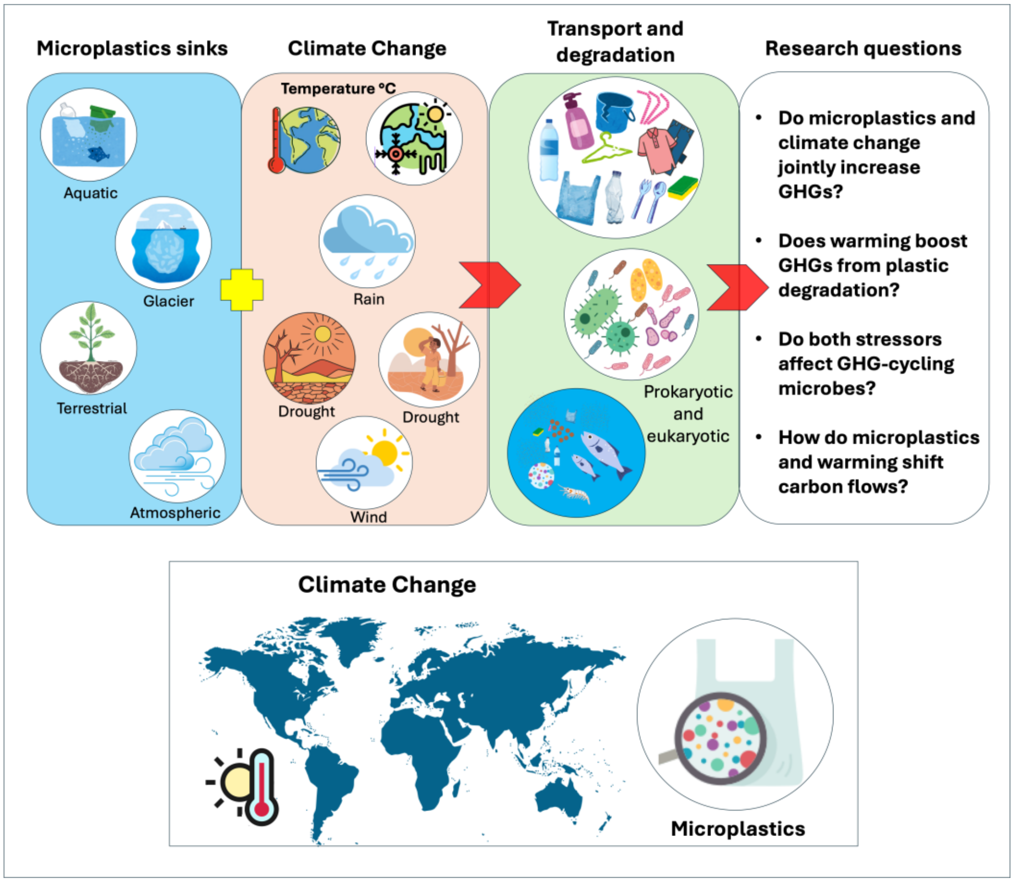

Figure 4. Interaction between MPs and CC. Microplastics accumulate in different environmental sinks (aquatic, terrestrial, glacial, and wind-borne). Climate change, through increased temperature, changes in precipitation patterns, droughts, and wind, can influence the transport and degradation of plastics. This, in turn, affects prokaryotic and eukaryotic organisms and alters carbon and GHG fluxes. Key research questions regarding the combined effects of microplastics and climate change on GHG emissions, microbial communities, and the global carbon cycle are highlighted. Illustration: N. Carabantes, LP. Suescún-Bolívar, and A. Santamaría-Miranda.

3.2 Effect of MPs on Greenhouse Gas Generation and Their Global Warming Potential

A 500 mL bottle of water you consume daily releases approximately 83 g of CO_2 during its production. Furthermore, over time, the plastic bottle can fragment into millions of MPs due to physical and biological processes, affecting nutrient cycles in terrestrial [1], [15] and aquatic [11] ecosystems. But can MPs cause climate change? (Fig. 4) MPs can intensify the physiological, biochemical, and molecular effects of temperature increases on organisms such as phytoplankton [11], zooplankton [26], plants [7], arthropods, birds, and worms, among others [reviewed in 1]. However, the synergistic effect between MPs pollution and global warming (GW) has only recently begun to receive scientific attention, so the following paragraphs will address these connections.

The short answer to the previous question is yes, the increase in emerging pollutants such as MPs in ecosystems directly contributes to climate change. Plastic production, transportation, handling, and degradation generate greenhouse gases (GHGs) [27], [12]. Furthermore, the physicochemical characteristics of MPs, together with the environmental conditions of soil and water [11], increase the production of GHGs, potentially exacerbating GW [25].

CC affects biodiversity and poses challenges for conservation, especially under anthropogenic pressures (Fig. 3 B, purple cluster). This situation is exacerbated by the increasing concentration of MPs in the water and sediments of aquatic and terrestrial ecosystems, as well as in remote regions such as the Arctic (Fig. 3 B, red cluster). The interaction between plastic pollution and thermal stress increases cytotoxicity in organisms (Fig. 3 B, green cluster). Furthermore, the ability of MPs to adsorb heavy metals and microorganisms favors the entry of allochthonous contamination, affecting water and soil quality (Fig. 3 B, green-yellow cluster). This transport mechanism facilitates the formation of specific microbial communities known as the plastisphere, some of which could be intervening in controlled biodegradation processes [6]. However, they could also promote the transfer of resistance genes and/or new metabolic pathways to communities of native microorganisms, intensifying the spread of multi-resistant pathogens, as well as the dynamics of nutrient retention and release in both water and soil. The disruption of biogeochemical cycles causes an increase in the release of CO_2, N_2O, and CH_4, three greenhouse gases with high potential to generate GW. This problem requires sustainable strategies for the management and recycling of plastic waste, which has increased with the use of protective materials during the recent COVID-19 pandemic (Fig. 3 B, blue cluster).

Metadata analysis shows that all MPs present in soils significantly increase the production of methane by 60%, carbon dioxide by 12%, and nitrous oxide by 11% [25]. These gases have a high potential to produce a global temperature increase. Furthermore, it was found that the chemical composition of MPs, their shape, size, and the percentage of soil contamination by MPs differentially favor GHG production. For example, the bioplastics polylactic acid (PLA), low-density polyethylene (LDPE), and polyethylene (PE) differentially favor CO_2 production (PLA>LDPE>PE); phenol formaldehyde (PF), low-density polyethylene, and polyurethane (PU) increase N_2O production (PF>LDPE>PU), while polystyrene (PS) reduces its production. Methane production is affected by PE and polystyrene (PS). If the soil is contaminated with more than 0.5% MPs, as well as the presence of fibers, beads, and films, with sizes between 10 and 500 µm, it causes an increase in GHG production [25].

In this sense, it can be highlighted that PE-based MPs with the sizes and shapes mentioned above are important due to their effect on increasing the emission of the main GHGs in the soil. Furthermore, policies and management plans should be developed to prevent soils from exceeding 0.5% of MPs pollution, as they induce GHG production.

Although MPs generally promote GHG production, some of their characteristics, combined with soil properties, have different GWPs. PLA, although the type of plastic with the greatest effect on CO_2 production, has the lowest GWP. Meanwhile, PF has the highest GWP, which increases even further if it is the component of a bead-shaped MPs. On the other hand, increasing the size of MPs favors GWP, but small sizes (10–100 µm) decrease GHG production [25].

The above could be explained because in soils contaminated by MPs, there is an increase in methanogenic microorganisms, which influences the increase in CH_4 production. Also, the overexpression of bacterial genes involved in denitrification and nitrification has been measured, favoring the production of N_2O [17], [28], [29]. Furthermore, changes in soil microbial communities and the increase in plastic-degrading microorganisms increase the demand for carbon sources, which causes an increase in soil respiration, and therefore a high production of CO_2 [25].

In the oceans, MPs have reached every imaginable corner, from the surface to the depths of the hadal benthos of the Mariana Trench (11,000 m deep), and from the tropics to the poles as part of ice cores [reviewed in 13]. They are also present in biota across all ocean regions, affecting their health and facilitating the transport of these particles into marine sediments.

In addition, events intensified by climate change, such as runoff, wastewater discharges, atmospheric deposition, fisheries, and the transport of water and sediment from rivers, are the main contributors to MPs accumulation. Ocean currents and thermohaline circulation (e.g., AMOC) disperse MPs globally, making the oceans the primary sinks. Increases in MPs concentration have been correlated with depth, ranging from 2 to 15 MPs * L^- in surface water to as high as 2000 MPs * L^- in deep-sea sediments [reviewed in 13].

MPs also directly and indirectly affect the physiology of phytoplankton, which is responsible for fixing half of the global annual carbon [reviewed in 13]. This compromises gas exchange and the C cycle in the ocean [11]. Because phytoplankton are primary producers, the base of food webs, they can transfer ingested MPs to zooplankton [30] and all organisms in food webs. This negatively impacts zooplankton digestion, growth, and reproduction, unbalanced carbon recycling, and jeopardizes the effective sequestration of carbon dioxide on the ocean floor.

Although the effects of MPs on GHG emissions in marine environments have not been quantified, as has been reported in the soil of terrestrial ecosystems and agroecosystems [25], there are measurements of increased methane and ethylene emissions when polyethylene is exposed to solar radiation [31]. Furthermore, the ocean is home to a broad and diverse microbiota, dominated by bacteria (and in some cases, fungi), responsible for driving global biogeochemical cycles through photo- and chemosynthesis, as well as the fixation and recycling of nutrients such as nitrogen, sulfur, and phosphorus [32], [33]. These microorganisms and the biochemistry of ocean sediments could be affected by MPs, making them a potential source of GHG emissions, but there is no field or experimental data on this potential threat. Therefore, this research approach represents a niche area of knowledge that should be explored at different geographic scales, from the local to the global.

4. Conclusion

Microplastic pollution represents a global environmental issue of a magnitude comparable to climate change, and both phenomena individually threaten the future of biodiversity and the health of ecosystems and humans. Plastics emit greenhouse gases throughout their life cycle, from their synthesis to their final disposal in landfills. Furthermore, the persistent increase in manufacturing and fragmentation of microplastics in aquatic and terrestrial ecosystems contribute to increased GHG emissions, disruption of carbon cycling and sequestration in both the ocean and soil. This alteration is associated with changes in sediment biochemistry caused by modifications in the microbial communities, humidity, aeration, and the aggregation of organic matter. However, this is a developing field of knowledge that urgently requires addressing through empirical research both in the field and in the laboratory. Based on the above, these studies will support preliminary findings and produce more precise estimates that explain the current and future impact of microplastics under anticipated climate change scenarios.

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