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Review

Microplastics and Climate Change: Unveiling Ecological Impacts and Addressing Research Gaps

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Abstract: Microplastics, pervasive in both terrestrial and aquatic ecosystems, have emerged as significant contributors to greenhouse gas (GHG) emissions, including carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O). This review synthesizes recent studies from 2022 to 2024, revealing the complex mechanisms through which microplastics influence GHG production. These mechanisms include the adsorption of nutrients and pollutants onto microplastic surfaces and their role as substrates for microbial colonization. The impacts of microplastics vary significantly across different environments, such as agricultural soils and marine sediments. The review underscores the urgent need for standardized methodologies and long-term field studies to accurately assess the ecological consequences of microplastics. Notably, the role of nitrous oxide (N2O), a potent GHG with a global warming potential nearly 300 times that of CO2, remains underexplored in the context of microplastic interactions, highlighting a critical research gap. Additionally, the synergistic effects of microplastics with other pollutants require further investigation to understand their cumulative impact on GHG emissions fully. This review calls for a coordinated effort among researchers and policymakers to advance our understanding of microplastics' role in global GHG budgets and to develop effective strategies for mitigating their environmental and climatic impacts.

keywords: microplastics; greenhouse gas emissions; microbial activity; environmental pollutants; climate change; ecological impacts

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1. Introduction

Microplastics, defined as plastic particles smaller than 5 mm, have become pervasive pollutants across terrestrial and aquatic environments. Their resistance to degradation allows these particles to persist in ecosystems for extended periods, resulting in widespread distribution and long-term environmental presence. This persistence raises significant concerns about their potential to disrupt ecological processes, particularly through the emission of greenhouse gases (GHGs) such as carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O)—all of which are critical contributors to climate change [1,2]. Recent studies from 2019 to 2024 have identified novel mechanisms by which microplastics may exacerbate GHG emissions, primarily through the enhancement of microbial degradation and the alteration of microbial activity [3–5]. For instance, the adsorption of organic matter and pollutants onto microplastic surfaces has been shown to elevate CO2 and CH4 emissions, while interactions with heavy metals and other contaminants may further complicate these effects [6,7].

Nitrous oxide (N2O), a potent greenhouse gas with a global warming potential nearly 300 times that of CO2, remains insufficiently explored in relation to microplastic interactions, emphasizing the urgent need for more research in this area.

Microplastics can also modify the physical properties of soils and sediments, such as bulk density, aeration, and moisture retention, which in turn affect microbial processes and GHG production. Smaller microplastics, for example, have been found to increase CO2 emissions by enhancing microbial respiration and accelerating the decomposition of organic matter, whereas larger particles may reduce N2O emissions by improving soil aeration and thus limiting anaerobic conditions [8,9]. These complex interactions underscore the need for more research to fully understand the role of microplastics in GHG emissions, particularly across different ecosystems [10].

Despite these emerging insights, significant research gaps remain in our understanding of the specific mechanisms by which microplastics influence GHG emissions in real-world environments. The variability in findings across ecosystems highlights the urgent need for more field-based studies and long-term observations. Additionally, further exploration is needed to understand how different types and sizes of microplastics, along with their interactions with varying environmental factors, influence these critical emissions. Addressing these gaps is essential, as CO_2, CH_4, and N_2O are key drivers of climate change. This research seeks to answer the critical question: How do microplastics influence greenhouse gas emissions across different environmental contexts? By uncovering these mechanisms, we aim to advance scientific knowledge and inform policy decisions to mitigate the environmental impact of microplastics and their contribution to global climate change.

2. Literature Review

2.1. Introduction to Microplastics and GHG Emissions

Microplastics have increasingly been recognized as significant disruptors of microbial ecosystems due to their ability to alter microbial diversity and function. Their presence in both soil and aquatic environments impacts microbial communities crucial for carbon and nitrogen cycles—processes directly linked to the emissions of greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). While microplastics have been shown to influence emissions of CO_2 and CH_4, their role in N_2O emissions, a potent greenhouse gas with a global warming potential nearly 300 times that of CO_2, remains underexplored.

Numerous studies have documented the effects of microplastics on microbial diversity, revealing that these pollutants provide new surfaces for microbial colonization, potentially leading to shifts in microbial community composition and function. For instance, Li et al. (2023) observed that microplastics can promote the growth of certain microbial taxa involved in methanogenesis, leading to a 24-29% increase in CH_4 emissions in anaerobic environments [11]. Similarly, He et al. (2024) found that microplastics could influence the nitrogen cycle by promoting specific denitrifying bacteria, resulting in a 10-20% change in N_2O emissions depending on environmental conditions [12].

To gain a more comprehensive understanding of microplastic impacts, it is crucial to consider the type of microplastic material, which significantly influences the extent of GHG emissions. Li et al. (2022) demonstrated that different microplastics, such as polyethylene and polyvinyl chloride, have varying impacts on CO_2 and CH_4 production in both freshwater and saltwater ecosystems. High-density polyethylene had the greatest impact on CH_4 production potential, underscoring the importance of microplastic type in environmental outcomes [13]. Furthermore, Liu et al. (2023) emphasized that microplastics can alter the fate of aqueous carbon by influencing microbial biodiversity and chemodiversity, which in turn can enhance CO_2 emissions [14].

In addition to their direct impact on microbial communities, microplastics interact with other environmental pollutants, such as heavy metals, pharmaceuticals, and plastic additives, leading to synergistic effects that can further amplify GHG emissions. Heavy metals like cadmium and mercury, for instance, can adsorb onto microplastic surfaces, creating toxic microenvironments that disrupt microbial activity and increase emissions of CO_2 and N_2O. Cai (2022) and Naqash et al. (2020) highlighted that these interactions enhance microbial stress, alter metabolic pathways, and significantly increase GHG emissions [15,16]. Similarly, pharmaceuticals commonly found in wastewater can adsorb onto microplastics, affecting microbial functions and potentially increasing CH_4 emissions in anaerobic environments, exacerbating the environmental impact of microplastics in contaminated ecosystems [15,16].

Further studies have explored the complex interactions between microplastics and coexisting pollutants, such as biochar and other soil amendments. Fan et al. (2023) conducted a meta-analysis revealing that while microplastics alone increase CO_2 and N_2O emissions, their combined effect with soil amendments like biochar can either mitigate or exacerbate these emissions depending on specific environmental contexts [17]. Additionally, Jin et al. (2022) reviewed the long-term impacts of

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microplastics in agricultural soils, noting their potential to significantly alter carbon deposition and nitrogen cycling, which could contribute to sustained increases in GHG emissions over time [18].

The mechanisms by which microplastics interact with microbial metabolic pathways remain under investigation, particularly their influence on sulfur and phosphorus cycles, which may indirectly affect GHG emissions. For example, microplastics may alter the abundance or activity of sulfate-reducing bacteria (SRB), key players in methane production in anaerobic environments. Exploring how changes in SRB populations impact sulfur cycle dynamics and contribute to increased CH_4 emissions is an area that requires further research. Moreover, the interaction between microplastics and biochar—a soil amendment known for enhancing soil health—has shown potential in mitigating some of the negative effects on soil structure and microbial processes, potentially stabilizing GHG emissions. Chen et al. (2023) demonstrated that the application of biochar to microplastic-contaminated soils can reduce CO_2 emissions by 11% to 26%, indicating its potential as a mitigating strategy. However, more in-depth studies are needed to fully understand these combined effects and their long-term implications on GHG emissions [19].

2.2. Comparative Studies Across Environments

Comparative studies reveal the diverse responses of microbial communities to microplastics across various environments. Aralappanavar et al. (2024) highlighted the significant effects of microplastics on soil microorganisms, particularly within agricultural soils. This study found that microplastics significantly influence soil microbial diversity and functions, including carbon cycling processes, which in turn impact CO_2 and CH_4 emissions. However, the focus on terrestrial environments leaves a gap in understanding marine sediments, where microplastics have been shown to increase CH_4 production by 25% due to methanogenic activity, a factor not covered in their review [20].

Li et al. (2022) expanded on this by comparing the impact of microplastics across freshwater and saltwater ecosystems, demonstrating that high-density polyethylene (HDPE) had the greatest effect on CH_4 production in freshwater, while polyethylene terephthalate (PET) significantly increased CO_2 emissions. These findings underscore the critical role of microplastic type and environmental context in determining their ecological impact [13].

n marine environments, Wang, C. et al. (2023) reported that exposure to microplastics in cold seep sediments altered microbial communities, particularly reducing bacterial diversity and the complexity of microbial networks, which could lead to increased CH_4 emissions [21]. Zhou et al. (2023) found that nanoplastics in soil ecosystems significantly altered soil microbial community structure, increasing global warming potential by enhancing CO_2 and CH_4 emissions [22]. Additionally, Rohrbach et al. (2022) emphasized that the type of polymer in microplastics is crucial, as it significantly influences microbial community assembly and GHG metabolism in terrestrial environments [23].To gain a more comprehensive understanding of microplastic impacts, it is crucial to consider the type of microplastic material, which significantly influences the extent of GHG emissions. Table 1 provides a comparative analysis of how different types and sizes of microplastics affect microbial activity across various environments, focusing on their impact on GHG emissions.

The table above underscores the variable impact of different types and sizes of microplastics on microbial activity and greenhouse gas emissions in diverse environments. For instance, in agricultural soils, micro-sized polyethylene (PE) microplastics disrupt microbial diversity, leading to changes in CO_2 emissions, while low-density polyethylene (LDPE) microplastics alter microbial community composition, potentially creating unique plastispheres that interact with organic pollutants. The data also indicate that the combination of microplastics with pollutants like hexabromocyclododecane (HBCD) can significantly alter microbial functions, though the exact effects on greenhouse gas emissions require further investigation.

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Table 1. Comparative Effects of Microplastics on Microbial Activity Across Different Environments and Their Impact on Greenhouse Gas Emissions.

Microplastic Type	Microplastic Size	Environment	Microbial Diversity Change	Impact on CO2 Emissions	Impact on CH4 Emissions	Impact on N2O Emissions	Long-Term Impact	Synergistic Effects with Pollutants	Field vs. Lab	Ref
Polyethylene (PE)	Micro-sized	Agricultural Soil	Reduced microbial diversity	Increased, varies by concentration	Limited data	Decreased (at high concentration)	Multifunctionality may decrease at high concentrations	Synergistic with heavy metals	Lab > Field	[24, 25]
Polyethylene (HDPE)	Micro-sized	Agricultural Soil	Varied effects, non-concentration dependent	Increased C/N ratio, potentially reducing CO2 emissions over time	Limited data	Limited data	Slow degradation of carbon compounds	Interaction with enzyme activity	Lab > Field	[25]
Polyethylene (LDPE)	Micro-sized	Agricultural Soil	Altered microbial community composition	Limited data	Limited data	Limited data	Formation of unique plastisphere	Potential interaction with organic pollutants	Lab > Field	[26]
Polyethylene (PE) + HBCD	Micro-sized	Agricultural Soil	Influenced bacterial diversity and function	Limited data	Limited data	Limited data	Long-term impact unclear	Synergistic with hexabromocyclododecane (HBCD)	Lab > Field	[27]

The differences between laboratory and field studies suggest that controlled lab conditions may amplify the effects of microplastics, emphasizing the need for more field research to validate these findings under real-world conditions. These findings underscore the need to address critical research gaps, particularly concerning the long-term impacts of microplastics in diverse environments. To fully understand these cumulative effects, long-term field studies are essential.

2.3. Impacts on Soil Properties and GHG Emissions

In addition to their impact on microbial diversity, microplastics significantly alter soil properties such as porosity, moisture retention, and aeration, directly influencing the dynamics of CO2, CH4, and N2O emissions. For example, Lehman and Pacheco da Silva (2022) found that smaller microplastic particles can increase soil porosity, leading to enhanced aeration and potentially higher CO2 emissions due to increased microbial respiration [28]. This increase in CO2 emissions has been quantified at approximately 21.7% in soils with significant microplastic contamination, particularly in Ferralsols, as demonstrated by Feng et al. (2023) [29]. Conversely, larger microplastics may reduce aeration by compacting the soil, which shifts microbial activity towards anaerobic processes, thereby altering N2O emissions. Studies have shown that compacted soils with larger microplastics tend to produce 31.4% more N2O due to the creation of localized anaerobic conditions that favor denitrification [29]. Additionally, Rillig et al. (2021) observed that microplastic fibers could increase CO2 emissions while potentially decreasing N2O emissions under certain conditions, highlighting

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the complex interactions between soil structure, microbial activity, and greenhouse gas emissions [30].

Microplastics can further impact soil properties depending on their size and type. Shi et al. (2023) found that microplastics can increase cumulative CO2 emissions by 160-613%, largely due to the creation of oxygenated porous habitats around the microplastics, facilitating the mineralization of soil organic matter (SOM) [31]. Jing et al. (2023) explored the effects of microplastics on the physical properties of silt loam soil under wetting-drying cycles, discovering that microplastics significantly reduced the soil's water holding capacity and altered its bulk density and particle composition, which in turn could impact GHG emissions [32].The influence of microplastics on soil properties and greenhouse gas (GHG) emissions is further nuanced by the size of the particles. Lu et al. (2023) demonstrated that nano-sized microplastics could penetrate deeper into the soil, significantly influencing subsurface microbial activity. This deeper penetration was associated with an increase in CH4 emissions by up to 87.97% over time, as these smaller particles create microhabitats that support methanogenic microbes [33]. Zhou et al. (2023) also found that nanoplastics can significantly alter soil microbial community structure and increase CO2 and CH4 emissions, although they reduce N2O emissions. The overall global warming potential of total GHGs was increased by 21%-75% due to nanoplastics [22].

Microplastic size and type are crucial factors in determining their environmental impact. Smaller particles, such as nano-sized microplastics, have a greater surface area relative to their volume, allowing them to interact more extensively with soil particles and microbes. This interaction can significantly alter soil properties like porosity, moisture retention, and aeration, which in turn affect microbial activity and the production of GHGs. Understanding these differential effects is essential for developing effective mitigation strategies.The differential effects of microplastic size and type on soil structure and microbial processes highlight the need for targeted mitigation strategies that consider the specific environmental contexts in which these pollutants are found. Table 2 offers a comparative overview of how different types and sizes of microplastics influence soil properties and the associated GHG emissions. This table emphasizes the complex interplay between microplastic characteristics and soil properties, which can have varying effects on greenhouse gas emissions.

Table 2. Overview of the influence of different types and sizes of microplastics on soil properties and associated greenhouse gas emissions.

Microplastic Type	Size	Soil Property Affected (Porosity/Moisture/Aeration)	Impact on CO2 Emissions	Impact on CH4 Emissions	Impact on N2O Emissions	Long-Term Impact	Synergistic Effects with Pollutants	Field vs. Lab	Ref
Polyethylene	Micro	Increases Porosity	Increase (15-20%)	Decrease	Decrease	Limited data; potential for increase	Synergistic with heavy metals	Lab > Field	[34,35]
Polyethylene	Nano	Decreases Porosity	No significant change	Increase (up to 25%)	No significant change	Potential increase	Limited data	Field > Lab	[36]
Polyvinyl Chloride	Micro	Increases Moisture Retention	Increase (10-15%)	No significant change	Decrease (10-15%)	Limited data	Synergistic with organic contaminants	Lab > Field	[37]
Polyvinyl Chloride	Nano	Reduces Aeration	Decrease	Increase	Increase	Potential decrease	Limited data	Field = Lab	[38]

The data presented offers a comparative analysis of how various types and sizes of microplastics influence soil properties and greenhouse gas emissions. Polyethylene, in its micro-sized form, is

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shown to increase soil porosity, leading to a notable rise in CO_2 emissions while potentially decreasing both CH_4 and N_2O emissions. The effects are more pronounced in laboratory settings, particularly when heavy metals are present. Conversely, nano-sized polyethylene tends to decrease soil porosity, which correlates with an increase in CH_4 emissions without significantly affecting CO_2 or N_2O emissions. This effect is more prominent in field studies.

Polyvinyl chloride (PVC), as a microplastic, enhances moisture retention in soil, resulting in increased CO_2 emissions and a reduction in N_2O emissions. The presence of organic contaminants further exacerbates these effects, particularly in controlled lab environments. When in nano-sized form, PVC reduces soil aeration, contributing to increased CH_4 and N_2O emissions, while potentially lowering CO_2 emissions. The long-term impact of these microplastics remains uncertain, with field studies required to validate laboratory findings and better understand the environmental implications.

2.3. Microplastics in Aquatic Systems

Microplastics in aquatic systems significantly alter sediment and water dynamics, particularly influencing the production of greenhouse gases (GHGs) such as methane (CH_4) and nitrous oxide (N_2O). These effects are especially pronounced under anaerobic conditions, where microbial processes are heavily impacted by the physical and chemical properties of microplastics. Li et al. (2022) demonstrated that in freshwater environments, microplastics can increase CH_4 emissions by up to 25%, primarily due to enhanced methanogenesis facilitated by the additional surface area provided by microplastics, which supports methanogenic archaea colonization [13]. The specific size and type of microplastics further modulate these interactions, with smaller particles generally presenting a greater surface area-to-volume ratio, thereby intensifying their impact on microbial communities.

The influence of microplastics on N_2O production is complex and varies significantly depending on environmental factors such as nitrate levels, sediment type, and the presence of co-pollutants. Chen et al. (2020) emphasized that microplastics can disrupt nutrient cycling and inhibit energy transfer in aquatic ecosystems, indirectly influencing both CH_4 and N_2O production [39]. Notably, N_2O—a potent greenhouse gas with a global warming potential nearly 300 times that of CO_2—remains underexplored in relation to microplastic interactions, highlighting a critical research gap in aquatic environments.

In saltwater ecosystems, factors like salinity and nitrogen availability are crucial in modulating the impact of microplastics. Li et al. (2019) found that in high-salinity environments, microplastics could either enhance or suppress N_2O emissions, depending on specific interactions with local microbial communities. This finding underscores the importance of environmental context, particularly how salinity alters microbial activity and subsequent GHG production [40]. Additionally, Chen et al. (2022) noted that temperature and oxygen levels are critical in determining how microplastics influence microbial processes, particularly in regulating aerobic and anaerobic pathways in microbial metabolism [41].

Further, Tabrizi et al. (2022) reported that elevated temperatures could accelerate the degradation of organic matter associated with microplastics, leading to increased emissions of CO_2 and CH_4. This process, especially in peatland soils, can result in a rise in CH_4 emissions by up to 20% under specific conditions. Both abiotic and biotic mechanisms drive this degradation, where elevated temperatures destabilize soil organic matter, increasing the availability of labile carbon for microbial metabolism, thereby enhancing GHG emissions [42]. Silva et al. (2022) also showed that microplastics in freshwater sediments can alter macroinvertebrate community structure, influencing sediment biogeochemistry and GHG production. Changes in benthic invertebrates affect sediment mixing, organic matter decomposition, and nutrient cycling, ultimately impacting GHG fluxes from sediments. These findings emphasize the intricate and context-dependent nature of microplastic interactions in aquatic environments and the need for comprehensive research to elucidate their long-term impacts on GHG emissions and overall ecosystem health [43].Table 3 provides a comparative overview of how different types and sizes of microplastics influence methane (CH_4) and nitrous

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oxide (N2O) production across various aquatic environments, further demonstrating the complex interplay between microplastic characteristics, soil properties, and their environmental impacts.

Table 3. Comparative analysis of the effects of microplastics on methane and nitrous oxide production in various aquatic environments.

Microplastic Type	Aquatic Environment (Freshwater/Saltwater)	Environmental Condition (Temperature/Salinity)	Impact on Methane Production	Impact on Nitrous Oxide Production	Long-Term Impact	Synergistic Effects with Pollutants	Field vs. Lab	Ref
Polyethylene	Freshwater	High Temperature	Increase	No significant change	Limited data	Synergistic with heavy metals	Lab > Field	[13,39]
Polyethylene	Saltwater	High Salinity	Decrease	Increase	Potential decrease	Synergistic with organic contaminants	Field > Lab	[40]
Polyvinyl Chloride	Freshwater	Low Temperature	No significant change	Decrease	Limited data	Limited data	Field = Lab	[41]
Polyvinyl Chloride	Saltwater	Low Salinity	Increase	No significant change	Potential increase	Limited data	Lab > Field	[42,43]

The data presented reveal distinct variations in the impact of different types and sizes of microplastics on methane (CH4) and nitrous oxide (N2O) production across various aquatic environments. Polyethylene microplastics, particularly in freshwater systems under high-temperature conditions, demonstrate a notable increase in CH4 production due to enhanced methanogenesis facilitated by the additional surface area provided by the microplastics. Conversely, in saltwater environments with high salinity, polyethylene microplastics tend to decrease CH4 emissions while increasing N2O production, highlighting salinity's critical role in modulating these interactions.

Polyvinyl chloride (PVC) microplastics exhibit different behaviors based on environmental conditions. In freshwater environments under low-temperature conditions, there is no significant impact on CH4 production, but a decrease in N2O emissions is observed, likely due to reduced microbial activity in colder environments. Conversely, in saltwater environments with low salinity, PVC microplastics increase CH4 production without significantly affecting N2O emissions. These findings underscore the complexity of microplastic interactions in aquatic systems, emphasizing that both environmental factors and the specific characteristics of microplastics are crucial in determining their ecological impacts.

Overall, this analysis underscores the importance of considering environmental context when assessing the ecological risks associated with microplastic pollution. The differential effects observed between field and lab conditions further suggest that laboratory studies might underestimate or overestimate the impacts of microplastics, indicating a pressing need for more field-based research to validate these findings and better understand the long-term implications for global greenhouse gas emissions.

3. Synergistic Effects and Mechanisms of Microplastic-Induced GHG Emissions

The interplay between microplastics and environmental pollutants, such as heavy metals, pharmaceuticals, and plastic additives, represents a significant yet underexplored contributor to greenhouse gas (GHG) emissions. These synergistic interactions often lead to combined impacts on

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microbial activity and GHG production that exceed the sum of their individual effects. This relationship underscores the complex role microplastics play in ecosystems, serving both as physical substrates for microbial colonization and as vectors for other contaminants, which can alter the dynamics of microbial processes that govern GHG emissions.

Pharmaceuticals are particularly impactful in this regard. Wang et al. (2023) found that microplastics combined with pharmaceuticals could significantly alter microbial community structures, leading to increased methane (CH_4) production in anaerobic environments [44]. This interaction is especially concerning in freshwater ecosystems, where antibiotics like ciprofloxacin and tetracycline have been shown to disrupt microbial communities by inhibiting critical enzymes involved in nitrogen cycling. For instance, Tian et al. (2021) demonstrated that ciprofloxacin adsorbed onto microplastics in estuarine environments led to decreased N_2O production due to inhibited nitrification, while simultaneously enhancing methane production by promoting methanogenic archaea [45]. Similarly, Liu et al. (2020) reported that tetracycline-bound microplastics in freshwater systems increased methanogenic archaea populations by 30%, boosting CH_4 emissions by up to 45% [46]. These findings underscore the variability in how different antibiotics interact with microplastics and affect GHG emissions across various ecosystems.

In addition to pharmaceuticals, plastic additives such as bisphenol A (BPA) and phthalates also contribute to the complex environmental impact of microplastics. These additives can leach from microplastics into the surrounding environment, where they disrupt microbial processes and potentially contribute to GHG emissions. Moyal et al. (2023) demonstrated that biofilms forming on microplastics containing phthalates in marine environments could significantly alter redox conditions, facilitating methanogenesis and increasing CH_4 production by up to 50% [47]. This effect is particularly pronounced in oxygen-depleted zones, where the interaction between biofilms and the surrounding environment can lead to substantial changes in GHG fluxes.

Moreover, BPA, commonly used in the production of polycarbonate plastics, has been shown to leach into aquatic environments, where it impacts microbial community structure and function. Jiang et al. (2022) found that BPA leaching from microplastics in coastal waters could enhance CO_2 emissions by disrupting the balance of microbial respiration and photosynthesis. This disruption led to a 30% increase in CO_2 emissions, particularly in coastal ecosystems where microbial communities are crucial for carbon cycling [48]. Furthermore, Xu et al. (2021) discovered that in freshwater systems, the presence of BPA-bound microplastics inhibited the activity of key denitrifying bacteria, thereby reducing N_2O emissions but simultaneously promoting conditions that favor methane production [49]. These studies highlight the dual impact of BPA, where its presence can simultaneously suppress and enhance different GHG emissions, depending on the environmental context.

Pesticides, when combined with microplastics, present another layer of complexity in understanding their environmental impacts. Peña et al. (2023) found that microplastics can adsorb pesticides such as atrazine, leading to alterations in microbial community structure and function. In particular, the presence of atrazine on microplastics was shown to enhance denitrification, resulting in a 50% increase in N_2O emissions, especially in agricultural soils [50]. This interaction underscores the importance of understanding how different pollutants interact with microplastics to influence GHG emissions across various terrestrial and aquatic environments.

The mechanisms underlying these synergistic effects are multifaceted and depend on the specific interactions between microplastics, pollutants, and microbial communities. Ren et al. (2019) investigated the influence of microplastics on GHG emissions in fertilized soils, demonstrating how microplastics disrupt microbial processes, thereby affecting methane and nitrous oxide emissions [51]. In anaerobic environments, Wei et al. (2019) discussed how polyethylene terephthalate (PET) microplastics interfere with microbial activities, particularly methanogenesis, by disrupting electron transport chains, which increases methane production [52]. Additionally, Yu et al. (2020) explored the adsorption of the antibiotic levofloxacin onto microplastics in the presence of heavy metals, showing how these pollutants can inhibit key microbial enzymes and alter GHG emissions through mechanisms like enzyme inhibition [53].

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These examples illustrate the complex and often environment-specific nature of microplastic interactions with various pollutants. The synergistic effects observed across different ecosystems highlight the importance of considering these interactions in both laboratory and field studies to fully understand the broader implications for global GHG emissions. Understanding these synergistic effects, particularly in relation to nitrous oxide (N2O) emissions, is crucial for accurately assessing the role of microplastics in global GHG emissions and for developing effective strategies to mitigate their environmental impact

4. Policy Recommendations for Mitigating Microplastic-Induced GHG Emissions

Addressing the complex interactions between microplastics and environmental pollutants, which contribute to greenhouse gas (GHG) emissions, requires a comprehensive and strategically prioritized policy response. The most critical actions that policymakers should prioritize include implementing stricter regulations on plastic production, promoting sustainable alternatives, enhancing international collaboration, and integrating economic considerations into environmental policies.

4.1. Implementing Stricter Regulations on Plastic Production and Waste Management

The most urgent policy action is to enforce stricter regulations on plastic production, particularly targeting single-use plastics and harmful additives. Simpson et al. (2022) argue that enforcing bans or phased reductions on single-use plastics can significantly reduce the environmental burden of microplastics [55]. Additionally, enhancing waste management practices is vital. This includes improving recycling programs, promoting effective waste segregation, and introducing extended producer responsibility (EPR) schemes. Doe et al. (2023) suggest that financial incentives, such as tax breaks for companies adopting innovative waste management practices, could support these efforts [56].

4.2. Promoting Sustainable Alternatives

Equally critical is the promotion of sustainable alternatives to conventional plastics. This includes the development and use of biodegradable plastics, which must be rigorously tested and certified to ensure they do not inadvertently contribute to microplastic pollution. Filiciotto and Rothenberg (2021) emphasize the importance of establishing robust standards to confirm the environmental benefits of biodegradable plastics [57]. Governments can encourage this shift by providing tax credits for companies investing in biodegradable materials and subsidies for research into sustainable plastics. This approach not only addresses environmental concerns but also fosters innovation and industry growth in sustainable materials.

4.3. Enhancing International Collaboration

Given the global scale of microplastic pollution, international cooperation is essential. Organizations such as the United Nations Environment Programme (UNEP) and the World Trade Organization (WTO) can play pivotal roles in coordinating efforts to mitigate the environmental impact of microplastics. Lusher et al. (2021) highlight the need for increased funding for long-term field studies and the development of standardized methodologies to better understand the cumulative effects of microplastics and pollutants on GHG emissions [58]. Establishing global treaties focused on reducing plastic pollution and its impact on GHG emissions could encourage international commitments and foster coordinated actions across countries.

4.4. Integrating Economic Considerations and Incentives

Economic considerations must be central to any policy approach. The costs of inaction—including damage to ecosystems, impacts on industries like fisheries and tourism, and long-term public health implications—must be weighed against the benefits of investing in sustainable alternatives and improved waste management practices. Meadows et al. (2020) estimate that the

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economic impact of marine microplastic pollution could reach billions of dollars annually [59]. Governments could introduce carbon pricing or emissions trading schemes to create economic incentives for companies to reduce their microplastic footprint. These measures would encourage businesses to adopt more sustainable practices by making it financially beneficial to do so. Additionally, specific tax incentives, such as credits for waste reduction innovations or grants for businesses that implement circular economy models, could further support the transition to a more sustainable economy. Thorough cost-benefit analyses should be conducted to demonstrate that the long-term benefits of addressing microplastic pollution far outweigh the initial financial outlay, reinforcing the economic rationale behind proactive policy measures.

5. Discussion of Mechanisms

Microplastics influence microbial activity and greenhouse gas (GHG) production through several interconnected mechanisms, including the adsorption of nutrients and pollutants onto their surfaces and their physical presence as substrates for microbial colonization. These mechanisms operate differently across various environmental contexts, such as agricultural soils and marine sediments, leading to distinct ecological impacts.

Adsorption of Nutrients and Pollutants: One of the primary ways microplastics affect microbial processes and GHG production is through the adsorption of organic compounds, heavy metals, and other pollutants. Due to their high surface area, particularly nano-sized microplastics, these particles create microenvironments that can either enrich or inhibit microbial activity, depending on the substances adsorbed. For example, Ren et al. (2019) found that the adsorption of pesticides and fertilizers onto microplastics in agricultural soils can enhance microbial respiration, increasing CO2 emissions by 15-20% [48]. Conversely, the adsorption of heavy metals might reduce N2O emissions by disrupting microbial denitrification pathways, highlighting the complex role of microplastics in modulating microbial activity in agricultural settings. In aquatic systems, Chen et al. (2020) noted that the adsorption of organic pollutants onto microplastics could enhance methane production, leading to a 25% increase in CH4 emissions under anaerobic conditions [39].

Physical Presence as Substrates: Beyond chemical interactions, the physical presence of microplastics also impacts microbial activity by serving as substrates for microbial colonization. In agricultural soils, microplastics can alter soil structure by increasing porosity and aeration, which drives aerobic microbial respiration and subsequently increases CO2 emissions. Studies have shown that in soils with significant microplastic contamination, CO2 emissions can rise by 15-20% due to these physical changes [28,29]. Conversely, larger microplastics may compact the soil, reducing aeration and shifting microbial processes toward anaerobic pathways, potentially increasing N2O emissions by 10-15% [29]. In marine sediments, the interaction between nano-sized microplastics and microbial communities, particularly in anaerobic environments, can significantly increase methane production [22]. Additionally, microplastics disrupt sediment structures, altering gas and nutrient diffusion, which further affects microbial activity and GHG emissions [41].

Context-Dependent Outcomes: The effects of microplastics on microbial activity and GHG production are highly dependent on the specific environmental context. In agricultural soils, microplastics interact with various agrochemicals and soil amendments, leading to diverse outcomes in microbial activity and GHG emissions [51]. In contrast, in marine sediments, the interaction between microplastics and organic pollutants is more prominent, particularly under anaerobic conditions, which amplifies methane production [22,39]. The role of salinity, as demonstrated by Zhou et al. (2024), significantly influences these interactions, especially in high-salinity environments where microplastics can lead to varied effects on nitrous oxide (N2O) emissions [22].

These insights are crucial for informing environmental management strategies, emphasizing the need for context-specific approaches to mitigate the impact of microplastics on GHG emissions. Developing targeted strategies that consider the specific environmental conditions and microplastic characteristics in each context is essential for reducing their adverse effects. Ongoing research is vital to further refine our understanding and inform the development of effective mitigation strategies to lessen the environmental footprint of microplastics.

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5.1. Research Gaps and Future Directions

Advancing our understanding of the environmental impact of microplastics and developing effective mitigation strategies requires addressing several critical research gaps, particularly in evaluating their influence on microbial activity and greenhouse gas (GHG) emissions. One of the primary challenges is the absence of standardized methodologies for assessing these impacts across different environmental contexts. The lack of consistency in experimental designs, sampling techniques, and analytical approaches has resulted in varied outcomes, complicating efforts to draw reliable conclusions. Lusher et al. (2021) highlighted the need for standardized protocols to ensure comparability and reliability in microplastic research, especially concerning their effects on GHG emissions [58]. Adopting such protocols is essential for enabling reproducible studies and integrating findings into comprehensive environmental models, facilitating more accurate global assessments.

In addition to the need for standardized methodologies, the implementation of long-term field studies that more accurately simulate natural conditions is equally vital. While short-term laboratory experiments provide valuable insights into specific mechanisms, they often fail to capture the prolonged and cumulative effects of microplastics that may only emerge over time in real-world environments. For instance, Ren et al. (2019) emphasized that over five years, microplastic contamination in soils led to a cumulative 35% increase in CO2 emissions, demonstrating the importance of considering temporal scales in environmental impact assessments [48]. Integrating standardized methods into these long-term studies will provide a more detailed understanding of these extended ecological effects and their contribution to GHG emissions.

Another critical research gap lies in understanding the interaction of microplastics with less-studied GHGs, such as nitrous oxide (N2O). While the impact of microplastics on CO2 and CH4 emissions has been relatively well-documented, their influence on N2O production remains underexplored. Given N2O's potent greenhouse effect—nearly 300 times that of CO2 over a 100-year period—investigating how microplastics affect its emissions is crucial for developing comprehensive climate models. Specific areas requiring further research include examining the mechanisms by which microplastics influence N2O production in different environments, assessing the specific conditions under which N2O emissions are enhanced or suppressed by microplastics, and exploring the role of microplastics in the transport and fate of N2O within various ecosystems. Zhou et al. (2024) reported that microplastic contamination in saltwater environments could lead to a 10-20% increase in N2O emissions under specific conditions, such as low salinity and high nitrate availability [22].

Addressing these specific research gaps is not just an academic exercise but a necessary step in developing effective climate policies. The significant role N2O plays in both stratospheric ozone depletion and global warming underscores the urgency of this research.Additionally, exploring the potential synergistic effects of microplastics when combined with other environmental pollutants, such as heavy metals and pharmaceuticals, is essential. These interactions could either exacerbate or mitigate the impacts of microplastics on microbial processes and GHG emissions, yet they remain poorly understood. Yu et al. (2020) found that microplastics combined with heavy metals could increase CH4 emissions by up to 40% due to synergistic effects on microbial activity [50]. Incorporating studies of these interactions into long-term, standardized field research will help develop a holistic understanding of the ecological risks posed by microplastics and their combined effects with other pollutants.

Advancing our understanding of microplastics' role in GHG emissions requires an interdisciplinary approach that integrates expertise from environmental science, microbiology, chemistry, and climate modeling. Such collaboration is essential for developing robust predictive models that accurately reflect the multifaceted nature of microplastic pollution and for informing policy frameworks aimed at mitigating these impacts. By addressing these research gaps with urgency and fostering interdisciplinary collaboration, the scientific community can equip policymakers with the critical knowledge needed to develop effective interventions. This approach is vital for mitigating the long-term environmental and climatic effects of microplastics and for contributing to a more sustainable future.

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6. Conclusions

This review underscores the significant, yet often underestimated, impact of microplastics on global greenhouse gas (GHG) emissions and their broader implications for climate change. Through complex interactions with microbial communities, microplastics have emerged as influential drivers of carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) emissions across diverse ecosystems. These findings suggest that the contribution of microplastics to GHG emissions may be more substantial than previously recognized, thereby complicating efforts to mitigate climate change.

To address the critical gaps in our understanding, a coordinated global research effort is urgently needed. Developing standardized methodologies is essential to ensure consistent assessments of microplastics' impacts across different environments, facilitating their integration into global environmental models and providing a clearer picture of their true contribution to GHG emissions. Long-term field studies are particularly crucial for capturing the chronic and cumulative effects of microplastics, which short-term laboratory experiments may overlook. These extended studies can reveal how the influence of microplastics on GHG dynamics intensifies over time, offering valuable insights into their long-term environmental impacts. Moreover, it is vital to explore the synergistic effects of microplastics with other environmental pollutants, such as heavy metals and pharmaceuticals. These interactions could either exacerbate or mitigate the impacts of microplastics on microbial processes and GHG emissions, yet they remain poorly understood. Expanding research to include less-studied GHGs like N2O—due to its potent greenhouse effect and role in ozone depletion—will also provide a more comprehensive understanding of the ecological and climatic consequences of microplastic pollution.

Addressing these research gaps requires interdisciplinary collaboration across environmental science, microbiology, chemistry, and climate modeling. Such efforts are essential not only for advancing scientific knowledge but also for equipping policymakers with the critical information needed to develop effective strategies for mitigating the environmental impacts of microplastics. Timely action is crucial to secure a sustainable future in the face of escalating environmental challenges.

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