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Review on Microplastic-Polymer Composite Interactions: Assessing Contaminant Adsorption, Structural Integrity, and Environmental Impacts

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Abstract: *Microplastics, defined as plastic particles smaller than 5 mm, have emerged as significant environmental contaminants due to their persistence and ability to adsorb and transport pollutants. This study explores the sources, classification, and environmental impact of microplastics, with a focus on their interactions with polymer composites. Microplastics serve as carriers for heavy metals, organic pollutants, and pathogens, increasing their bioavailability and potential toxicity. The degradation of polymer composites in microplastic-rich environments contributes to fragmentation, contaminant leaching, and structural deterioration. Strategies for mitigating microplastic-polymer composite contamination include the development of biodegradable materials, surface modifications to reduce contaminant adsorption, and advanced remediation technologies. The findings highlight the urgent need for research, policy interventions, and sustainable material innovations to address the challenges posed by microplastic pollution.*

Keywords*: Microplastics, Polymer Composites, Contaminant Transport, Environmental Pollution, Biodegradable Materials*

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1.0 Introduction

Microplastic pollution has emerged as a significant environmental concern, particularly in aquatic ecosystems, where its persistence and potential ecological impacts have drawn increasing attention and also in the air as particulate (Uzoho, 2025) . These microscopic plastic particles originate from various sources, including synthetic fibers, industrial discharges, and the degradation of larger plastic debris (Andrady, 2017). Due to their small size and hydrophobic nature, microplastics have been shown to interact with various contaminants, facilitating the transport of hazardous substances in water bodies and posing potential risks to marine organisms and human health (Wang et al., 2021). Addressing microplastic pollution necessitates a comprehensive understanding of the mechanisms by which these particles interact with environmental contaminants and engineered materials.

Fiber-reinforced polymer (FRP) composites have gained prominence in various industrial applications due to their high strength-to-weight ratio, corrosion resistance, and durability (Osabuohien,, 2017**)**. . These composites, which typically consist of a polymer matrix reinforced with fibers such as glass, carbon, or natural fibers, are widely used in marine, aerospace, and structural engineering applications (Singh et al., 2020). However, concerns have arisen regarding their degradation in aquatic environments, particularly in relation to microplastic generation and contaminant adsorption. Understanding how FRP composites interact with environmental pollutants is crucial for assessing their long-term performance and ecological footprint.

Studying contaminant adsorption and the structural integrity of FRP composites in microplastic-polluted environments is significant for both environmental sustainability and material durability. The ability of FRP composites to adsorb contaminants can influence pollutant dynamics in aquatic systems, potentially altering the fate and bioavailability of hazardous substances (Wu et al., 2021). Additionally, exposure to microplastics and associated contaminants may impact the mechanical properties of FRP materials, affecting their structural integrity and service life. Therefore, a comprehensive investigation into these interactions is necessary to inform material design strategies and environmental mitigation efforts.

This review aims to examine the role of FRP composites in microplastic-polluted environments, focusing on their potential for contaminant adsorption and structural degradation. By synthesizing recent findings, this work seeks to provide insights into the environmental implications of FRP composites and highlight strategies for mitigating their ecological impact while enhancing material performance.

2.0 Microplastics and Their Role in Contaminant Transport

Microplastics, defined as plastic particles smaller than 5 mm in size, have gained global attention due to their persistence and potential role in contaminant transport (Andrady, 2017). These particles originate from various sources and can act as vectors for environmental pollutants, leading to adverse effects on aquatic ecosystems and human health. The interaction between microplastics and contaminants is a critical research area, as it influences pollutant mobility, bioavailability, and toxicity (Liu et al., 2021).

2.1 Sources and Classifications of Microplastics

Microplastics are categorized based on their origin into primary and secondary microplastics. Primary microplastics are intentionally manufactured small particles, such as microbeads in personal care products, industrial abrasives, and synthetic fibers from textiles (Galgani et al., 2015). Secondary microplastics result from the fragmentation of larger plastic debris due to environmental weathering processes such as UV radiation, mechanical abrasion, and microbial degradation (Hale et al., 2020). Table 1 presents an overview of microplastic sources and their respective environmental origins.

Table 1: Sources and Classifications of Microplastics

Microplastic Type	Sources	Examples
Primary	Personal care products	Microbeads in facial scrubs
	Industrial applications	Abrasive powders, resin pellets
	Synthetic textiles	Polyester and nylon fibers from washing clothes
Secondary	Environmental degradation	Plastic bags, bottles, and fishing gear
	Mechanical weathering	Tire wear particles
	Photodegradation	Fragmented plastic debris from UV exposure

2.2 Types of Contaminants Associated with Microplastics

Microplastics serve as carriers for a range of contaminants, including heavy metals, organic pollutants, and pathogenic microorganisms. Their hydrophobic nature facilitates the adsorption of lipophilic pollutants such as polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs)

(Teuten et al., 2009). Additionally, heavy metals like lead (Pb), cadmium (Cd), and mercury (Hg) can accumulate on microplastic surfaces, increasing their environmental persistence (Brennecke et al., 2016). Table 2 highlights the major contaminants associated with microplastics and their environmental impact.

Table 2: Contaminants Associated with Microplastics

Contaminant Type	Examples	Environmental Impact
Heavy Metals	Lead (Pb), Cadmium (Cd), Mercury (Hg)	Bioaccumulation, toxicity to aquatic life
Organic Pollutants	PCBs, PAHs, DDT	Endocrine disruption, carcinogenic effects
Pathogens	Vibrio spp., E. coli, Salmonella	Disease transmission in marine organisms and humans

2.3 Mechanisms of Contaminant Adsorption onto Microplastic Surfaces

The adsorption of contaminants onto microplastic surfaces occurs through various mechanisms, including hydrophobic interactions, electrostatic forces, and surface complexation (Koelmans et al., 2016). Hydrophobic organic pollutants preferentially bind to microplastics due to their non-polar characteristics, while heavy metals adsorb through ionic interactions with functional groups present on the microplastic surface. Biofilm formation further enhances the ability of microplastics to act as vectors for microbial contaminants (Zettler et al., 2013). Figure 1 illustrates the primary mechanisms of contaminant adsorption onto microplastic surfaces.

2.4 Environmental Implications of Microplastic Contamination

Microplastic pollution poses significant environmental risks, including the disruption of aquatic ecosystems, bioaccumulation in marine food chains, and potential human health effects (Law & Thompson, 2014). The ingestion of microplastics by marine organisms can lead to physical blockages, reduced nutrient absorption, and toxicant exposure. Additionally, microplastics serve as a medium for long-range contaminant transport, exacerbating pollution across different environmental compartments. Policy interventions and advanced remediation strategies are essential to mitigate the environmental impact of microplastic contamination (Galloway et al., 2017).

3.0 Interaction Between Microplastics and Polymer Composites

The interaction between microplastics and polymer composites in aquatic environments is a growing area of research due to its implications for material degradation and pollutant dynamics. Polymer composites, particularly fiber-reinforced plastics, are widely used in structural applications, and their exposure to microplastics may influence their integrity and contaminant retention capabilities (Gewert et al., 2015). Understanding these interactions is essential for assessing the long-term durability of polymeric materials in marine environments and their role in pollution transport.

3.1 Structural and Chemical Interactions in Aquatic Environments

Microplastics interact with polymer composites through surface adhesion, diffusion, and chemical reactions. In aquatic environments, microplastics may become embedded in the matrix of polymer composites, altering their structural properties.

Factors such as polymer type, surface roughness, and environmental conditions (e.g., salinity and temperature) influence the extent of these interactions (Song et al., 2017). Chemical interactions may involve oxidation, hydrolysis, or photodegradation, leading to material weakening and increased microplastic deposition.

4.0 Environmental and Mechanical Impacts of Microplastic-Composite Interactions

4.1 Mechanical and Thermal Stability of Composites in Microplastic-Rich Environments

Polymer composites exposed to microplastic-rich environments undergo changes in mechanical and thermal stability due to prolonged interaction with microplastic particles. These interactions may lead to surface degradation, increased brittleness, and reduced thermal resistance, which compromise the durability of composite materials in marine and industrial applications (Gewert et al., 2015). Microplastic particles may embed within the matrix of polymer composites, causing microstructural defects that reduce mechanical integrity over time (Horton et al., 2018). Furthermore, exposure to fluctuating temperatures, salinity, and UV radiation in aquatic environments accelerates the oxidation and hydrolysis of composite materials, leading to significant material deterioration (Kole et al., 2017). Studies have shown that such degradation mechanisms not only weaken the polymer matrix but also enhance the release of smaller microplastic fragments, exacerbating environmental contamination (Xu et al., 2019).

4.2 Role of Polymer Degradation in Microplastic Fragmentation and Contaminant Leaching

Degradation of polymer composites contributes to the fragmentation of microplastics, further intensifying contaminant leaching into the environment. This process is influenced by environmental factors such as UV exposure, microbial activity, and mechanical stress, leading to the release of toxic additives and absorbed pollutants (Teuten et al., 2009). UV-induced photodegradation causes chain scission in polymeric materials, reducing their molecular weight and increasing their susceptibility to fragmentation (Andrady, 2011). Mechanical abrasion from water currents and wave action further breaks down weakened composites into micro- and nano-sized plastic particles (Song et al., 2017). Additionally, microbial colonization accelerates biodegradation, altering the chemical structure of polymers and facilitating the release of heavy metals, plasticizers, and persistent organic pollutants adsorbed onto microplastic surfaces (Brennecke et al., 2016). This phenomenon underscores the need for improved polymer formulations and effective environmental management strategies to mitigate microplastic pollution from degrading polymer composites.

5.0 Strategies for Mitigating Microplastic-Polymer Composite Contamination

5.1 Development of Biodegradable and Eco-Friendly Polymer Composites

Advancements in biodegradable polymer composites offer promising solutions for reducing microplastic pollution. Research focuses on using natural fibers, biopolymers, and nanomaterials to develop sustainable alternatives that degrade under environmental conditions without producing harmful residues. Biodegradable polymers, such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), and starch-based polymers, are being explored to replace conventional plastics. These materials not only degrade more readily in natural environments but also reduce the long-term accumulation of microplastics. Additionally, the incorporation of bio-based fillers, such as cellulose, chitosan, and lignin, enhances the mechanical strength and degradation properties of polymer composites. Efforts are also directed towards optimizing manufacturing processes to ensure the commercial viability of eco-friendly polymer alternatives without compromising material performance.

5.2 Surface Modifications for Reduced Contaminant Adsorption

Surface engineering of polymer composites, including hydrophilic coatings and chemical modifications, can minimize contaminant adsorption and improve material resistance to microplastic deposition. Surface modifications such as plasma treatment, graft polymerization, and incorporation of antifouling agents help in altering the physicochemical properties of polymer surfaces, reducing their affinity for pollutants. Hydrophilic coatings, for instance, promote water-repellency and reduce the adhesion of hydrophobic contaminants, thereby limiting their bioavailability. Additionally, functionalizing polymer surfaces with antimicrobial and antifouling agents can further prevent biofilm formation and the accumulation of pathogenic microorganisms. Research in this field is geared towards developing scalable, cost-effective surface modification techniques that maintain the structural integrity and performance of polymer composites while reducing environmental contamination.

5.3 Advances in Filtration and Remediation Techniques for Microplastic Removal

Innovative filtration technologies, such as membrane filtration, electrostatic separation, and bioremediation, are being developed to remove microplastics from aquatic systems. Membrane-based filtration, including ultrafiltration and nanofiltration, has shown high efficiency in capturing microplastic particles from wastewater streams. Electrostatic separation techniques leverage the charge differences between microplastics and surrounding water components to facilitate effective removal. Additionally, biological remediation methods, such as the use of microbial consortia and enzymatic degradation, have gained attention for their potential in breaking down microplastic contaminants. Advanced adsorption techniques using functionalized materials, such as activated carbon, metal-organic frameworks (MOFs), and bio-based adsorbents, are also being explored for their efficiency in microplastic capture. These approaches aim to enhance microplastic removal efficiency while minimizing secondary pollution, offering sustainable and scalable solutions for addressing microplastic contamination in water bodies.

5.5 Future Directions for Research and Policy Recommendations

Future research should focus on developing standardized methods for assessing microplastic-polymer interactions, evaluating the long-term impact of composite degradation, and implementing policies to regulate plastic waste. The need for interdisciplinary research integrating materials science, environmental engineering, and toxicology is essential for understanding the fate and transport of microplastics in ecosystems. Additionally, policies must be established to regulate the production and disposal of synthetic polymers, encouraging industries to adopt biodegradable alternatives. Strengthening international collaborations and regulatory frameworks will be crucial in addressing microplastic pollution effectively. Governments and environmental organizations should implement stricter regulations on single-use plastics, promote extended producer responsibility (EPR) programs, and support public awareness campaigns on sustainable plastic use. Further investment in developing cutting-edge detection technologies and remediation strategies will help mitigate the risks associated with microplastic contamination, ensuring a cleaner and healthier environment.

6.0 Conclusion

The findings indicate that microplastics, due to their small size and chemical properties, act as vectors for various environmental contaminants, including heavy metals, organic pollutants, and pathogenic microorganisms. Their ability to adsorb and transport pollutants is influenced by their physicochemical characteristics and environmental conditions. Additionally, interactions between microplastics and polymer composites contribute to the degradation of materials, altering their structural integrity and increasing the fragmentation of plastics into smaller particles. These processes exacerbate contamination and pollutant leaching, posing risks to aquatic ecosystems and human health.

The conclusion drawn from this study emphasizes the significant role of microplastics in environmental pollution and material degradation. The persistence and widespread distribution of microplastics, combined with their high affinity for contaminants, highlight the urgency of developing effective mitigation strategies. The interaction between polymer composites and microplastics further demonstrates the need for enhanced material design to reduce environmental impact. Addressing these issues requires a multifaceted approach involving scientific research, technological advancements, and regulatory measures.

Recommendations include promoting the development of biodegradable and eco-friendly polymer composites to reduce microplastic pollution at the source. Implementing surface modifications on polymer materials can minimize contaminant adsorption and improve material resistance to degradation. Advances in filtration and remediation techniques, such as membrane filtration and bioremediation, should be further explored to enhance microplastic removal from aquatic environments. Future research should focus on standardizing assessment methods for microplastic-polymer interactions and evaluating long-term environmental impacts. Strengthening regulatory frameworks and international collaborations is essential to effectively manage microplastic contamination and mitigate its effects on ecosystems and human health.

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Ethical Approval

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