European International Journal of Multidisciplinary Research and Management Studies

TYPE Original Research
PAGE NO. 114-119

Microplastics Across Environmental Pathways: Detection, Transformation, Human Exposure, and Emerging Biodegradation Strategies

Dr. Alejandro Moreno

Department of Environmental Science, Universidad de Valencia, Spain

OPEN ACCESS

SUBMITED 01 October 2025
ACCEPTED 15 October 2025
PUBLISHED 31 October 2025
VOLUME Vol.05 Issue10 2025

Abstract Microplastic pollution has emerged as one of the most complex and pervasive environmental challenges of the twenty-first century, transcending ecosystem boundaries and raising concerns about long-term ecological integrity and human health. Originally recognized as a marine contamination issue, microplastics are now understood to circulate across marine, freshwater, terrestrial, and atmospheric systems, ultimately intersecting with human food chains and industrial processes. This article presents an extensive and integrative examination of microplastics based strictly on existing scholarly literature, focusing on their environmental occurrence, analytical detection methods, physicochemical transformation, interaction with biological systems, and emerging remediation and biodegradation strategies. Particular attention is given to marine microplastics as contaminants, detection advances such as Nile Red staining, physicochemical surface modification processes, contamination of commercial table salts, and the implications of chronic dietary exposure in the context of global sodium consumption. The article further explores the role of waste management practices, mineral-industrial interfaces, soil and freshwater transport dynamics, and recent advances in microbial degradation of synthetic polymers. By synthesizing insights from environmental chemistry, materials science, toxicology, microbiology, and public health perspectives, this work highlights critical knowledge gaps, methodological uncertainties, and future research directions. The findings underscore that microplastic pollution is not a singular environmental problem but a systemic phenomenon requiring coordinated analytical, regulatory, and biotechnological responses. This comprehensive review aims to contribute a theoretically grounded and policy-

relevant framework for understanding microplastics as persistent, evolving, and biologically interactive contaminants with far-reaching implications for future generations.

Keywords: Microplastics, Environmental contamination, Detection methods, Human exposure, Biodegradation, Polymer transformation

Introduction

The The proliferation of plastic materials since the mid-twentieth century represents one of the most transformative industrial developments in human history. Plastics have become indispensable due to their durability, versatility, and low cost, finding applications across packaging, construction, medicine, agriculture, and consumer goods. However, these same attributes have contributed to an escalating environmental burden, as plastic waste accumulates and fragments rather than fully decomposes. Microplastics, commonly defined as plastic particles smaller than five millimeters, have emerged as a critical focus within environmental research because of their persistence, mobility, and biological accessibility (Cole et al., 2011).

Early scientific concern regarding microplastics centered on marine environments, where plastic debris was observed to fragment under ultraviolet radiation, mechanical abrasion, and biological activity. Cole et al. (2011) established that microplastics are not merely passive debris but active contaminants capable of interacting with marine organisms at multiple trophic levels. These interactions extend beyond physical ingestion, encompassing chemical vectoring of persistent organic pollutants and metals, as well as potential endocrine-disrupting effects. Over time, the conceptualization of microplastics has expanded from isolated marine litter to a ubiquitous environmental contaminant present in freshwater systems, soils, atmospheric fallout, and food products.

The growing recognition of microplastics in consumables such as table salt has intensified concerns about chronic human exposure. Studies reviewing microplastic contamination in commercial salts demonstrate significant variability and uncertainty, reflecting both methodological challenges and differences in source environments (Lee et al., 2021). This issue intersects with broader dietary considerations, particularly global sodium consumption patterns and associated cardiovascular risks, suggesting that microplastic intake may be embedded within existing public health frameworks rather than representing an isolated exposure pathway (Mozaffarian et al., 2014).

Simultaneously, advancements in analytical chemistry have revealed the complexity of identifying and quantifying microplastics, especially at smaller size ranges approaching nanoplastics. Techniques such as Nile Red staining have enhanced detection sensitivity, enabling the identification of particles previously overlooked by conventional visual methods (Erni-Cassola et al., 2017). Complementary to detection, research on polymer surface modification, weathering, and wettability has demonstrated that environmental exposure alters microplastic properties, influencing their transport, aggregation, and biological interactions (El-Saftawy et al., 2014; Benke et al., 2022).

Despite increasing awareness, significant gaps remain in understanding the full life cycle of microplastics, from production and fragmentation to environmental fate and potential remediation. The persistence of conventional thermoplastics poses particular challenges, prompting growing interest in biotechnological degradation strategies. Recent studies have identified diverse microbial consortia capable of colonizing and partially degrading polymers such as polyethylene, polystyrene, and polyethylene terephthalate, though practical scalability remains uncertain (Wei et al., 2020; Xiang et al., 2023).

This article addresses these interconnected dimensions by synthesizing existing literature into a unified, theoretically elaborated narrative. Rather than summarizing discrete findings, it explores the underlying mechanisms, uncertainties, and implications that define microplastics as a systemic environmental issue. Through this approach, the article seeks to clarify the current state of knowledge, identify critical limitations, and articulate future research priorities necessary for managing microplastic pollution across environmental and human health contexts.

Methodology

The methodological approach underlying this article is grounded in comprehensive qualitative synthesis rather than experimental data generation. The study adopts an integrative review framework, drawing exclusively from peer-reviewed literature, government reports, and authoritative scientific reviews provided in the reference list. This approach allows for deep theoretical elaboration across disciplines while maintaining strict adherence to established empirical findings.

Primary emphasis was placed on studies addressing microplastic occurrence, detection, physicochemical transformation, environmental transport, biological interaction, and remediation. Marine-focused research formed the foundational context, particularly the conceptualization of microplastics as contaminants rather than inert debris (Cole et al., 2011; Galloway and Lewis, 2016). Detection methodologies were analyzed through studies introducing and validating advanced analytical techniques, including fluorescence-based staining and thermal characterization, to understand both their capabilities and limitations (Erni-Cassola et al., 2017; Ivleva, 2021; Sorolla-Rosario et al., 2022).

Human exposure pathways were examined indirectly through studies on commercial table salt contamination and dietary sodium consumption. Governmental data from the Salt Department of India provided industrial and production context, while critical reviews assessed uncertainty and variability in reported contamination levels (GOI, 2017; Lee et al., 2021). Rather than quantifying exposure, the analysis focused on conceptual integration of microplastic intake within broader nutritional and public health paradigms (Mozaffarian et al., 2014).

Environmental transformation processes were explored through materials science literature examining polymer surface modification, weathering, wettability, and interaction with soils and sediments. These studies were treated as mechanistic insights into how microplastics evolve after environmental release, influencing mobility and bioavailability (El-Saftawy et al., 2014; Chiou and Hsieh, 2015; Shafea et al., 2023).

Finally, biodegradation and remediation strategies were analyzed through microbiological and biotechnological research identifying microbial consortia and enzymatic pathways capable of interacting with synthetic polymers. The methodological focus here was comparative and conceptual, emphasizing feasibility, constraints, and scalability rather than performance metrics (Wei et al., 2020; Urbanek et al., 2021; Xiang et al., 2023).

Throughout the analysis, methodological uncertainty, detection bias, and interdisciplinary disconnects were explicitly addressed to avoid overgeneralization. The absence of quantitative synthesis was intentional, reflecting both the heterogeneity of methods across studies and the article's objective to provide a theoretically expansive, publication-ready narrative grounded in existing evidence.

Results

The synthesized findings from the reviewed literature reveal microplastics as dynamic contaminants whose behavior and impacts vary across environmental compartments. In marine environments, microplastics are consistently identified as widespread and persistent, with documented ingestion by plankton, invertebrates, fish, and higher trophic organisms. Cole et al. (2011) demonstrated that microplastics are present across size classes and polymer types, indicating multiple sources and fragmentation pathways. These particles exhibit the capacity to adsorb hydrophobic pollutants, transforming them into mobile vectors of chemical exposure.

Advances in detection methodologies have significantly altered the perceived abundance of microplastics. The introduction of Nile Red staining enabled the identification of particles as small as twenty micrometers, revealing that earlier studies likely underestimated contamination levels (Erni-Cassola et al., 2017). Thermal and spectroscopic techniques further refined polymer identification, highlighting the diversity of plastics present in environmental samples and the prevalence of both semicrystalline and amorphous structures (Sorolla-Rosario et al., 2022).

Commercial table salts emerged as a notable intersection between environmental contamination and human consumption. Reviews of salt products from multiple regions reported microplastic presence with considerable variation, reflecting differences in source water, processing methods, and analytical protocols (Lee et al., 2021). While direct health outcomes were not established, the findings confirm that microplastics have entered routine dietary pathways. When contextualized alongside global sodium consumption patterns, this suggests that microplastic intake may be continuous and cumulative rather than sporadic (Mozaffarian et al., 2014).

Physicochemical transformation of microplastics was shown to be a critical determinant of environmental behavior. Surface modification studies demonstrated that exposure to radiation, weathering, and mechanical stress alters polymer roughness, wettability, and surface energy (El-Saftawy et al., 2014; Benke et al., 2022). These changes influence aggregation with organic matter, sedimentation rates, and microbial colonization, thereby affecting environmental distribution and persistence.

Terrestrial and freshwater studies expanded the scope of microplastic contamination beyond oceans. Investigations near open dumpsites revealed diverse plastic fragments embedded in soils, emphasizing the role of waste management practices in generating secondary microplastics (Ibor et al., 2023). Soil-focused research indicated that microplastics modify pore structure, water conductivity, and surface wettability, suggesting potential impacts on soil function and agricultural productivity (Shafea et al., 2023).

Biodegradation research provided cautious optimism. Multiple studies identified bacteria and microbial consortia capable of colonizing and partially degrading polymers such as polyethylene, polystyrene, and polyethylene terephthalate (Park and Kim, 2019; Hou et al., 2022; Xiang et al., 2023). However, degradation rates remained slow, often requiring pre-treatment or specific environmental conditions. Reviews emphasized that while biotechnological approaches hold promise, they are unlikely to fully offset ongoing plastic production without systemic changes (Wei et al., 2020).

Discussion

The integrated findings underscore that microplastic pollution is not a static phenomenon but an evolving environmental process shaped by material properties, environmental conditions, and biological interactions. One of the most significant conceptual shifts highlighted by the literature is the recognition of microplastics as active participants in environmental systems rather than inert residues. Their ability to adsorb pollutants, host microbial communities, and undergo physicochemical transformation positions them as complex vectors within ecological and biogeochemical cycles (Galloway and Lewis, 2016).

Detection advances, while transformative, also introduce new challenges. Increased sensitivity inevitably raises questions about comparability across studies conducted with different methodologies. The variability observed in salt contamination studies, for example, may reflect methodological inconsistency as much as genuine environmental differences (Lee et al., 2021). This uncertainty complicates risk assessment and underscores the need for standardized protocols, particularly as microplastics approach the nanoscale where detection becomes increasingly difficult (Ivleva, 2021).

The intersection of microplastic exposure with dietary sodium consumption illustrates the difficulty of isolating microplastics as a discrete health risk. Sodium intake is already embedded within cardiovascular risk frameworks, and microplastic ingestion through salt represents an additional, poorly characterized exposure layered onto existing concerns (Mozaffarian et al., 2014). This raises broader questions about cumulative and synergistic effects, especially given the potential for microplastics to carry chemical additives or environmental pollutants.

From a materials science perspective, the transformation of microplastics through weathering and surface modification has profound implications. Changes in wettability and surface energy influence not only environmental transport but also biological interactions, including microbial adhesion and enzymatic access (Chiou and Hsieh, 2015; Benke et al., 2022). These findings suggest that environmental aging may paradoxically increase both ecological risk and biodegradation potential, depending on context.

Biodegradation research highlights both promise and limitation. While numerous microorganisms demonstrate the capacity to interact with plastics, complete mineralization remains rare and slow. Reviews caution against viewing biodegradation as a standalone solution, emphasizing instead its role within integrated waste management and material redesign strategies (Wei et al., 2020; Taghavi et al., 2021). The exploration of cold-adapted and landfill-derived microbes expands the conceptual toolkit but also underscores the complexity of translating laboratory findings into real-world applications (Urbanek et al., 2021).

Future research must therefore balance optimism with realism. Addressing microplastic pollution requires coordinated efforts spanning material innovation, analytical standardization, waste management reform, and public health integration. The literature reviewed here collectively argues that without reducing plastic production and improving end-of-life management, downstream remediation efforts will remain insufficient.

Conclusion

Microplastics represent a defining environmental challenge of contemporary society, characterized by persistence, ubiquity, and complexity. The literature synthesized in this article demonstrates that microplastics traverse environmental boundaries, undergo continuous transformation, and intersect with biological and human systems in multifaceted ways. Advances in detection have revealed the extent of contamination, while materials science and microbiology have illuminated mechanisms of interaction and potential degradation.

However, these scientific advances also expose profound uncertainties. Variability in detection, incomplete understanding of health implications, and limited scalability of remediation strategies highlight the need for caution in interpretation and ambition in future research. Microplastics cannot be effectively addressed through isolated technological fixes; they require systemic responses integrating scientific insight with policy, industry, and societal change.

By framing microplastics as dynamic contaminants embedded within broader environmental and public health contexts, this article contributes to a more nuanced understanding of the problem. Continued interdisciplinary research, grounded in methodological rigor and theoretical depth, is essential for developing sustainable strategies capable of mitigating microplastic pollution for future generations.

References

1. Benke, A., Sonnenberg, J., Oelschlägel, K., Schneider, M., Lux, M., & Potthoff, A. Wettability after artificial and natural weathering of polyethylene terephthalate. Environments, 2022, 9, 134.

2. Charnock, C. A simple and novel method for the production of polyethylene terephthalate containing agar plates for the growth and detection of bacteria able to hydrolyze this plastic. Journal of Microbiological Methods, 2021, 185, 106222.

3. Chiou, C.-H., & Hsieh, S.-J. Empirical study and prediction of contact angle and surface free energy of commonly used plastics with pillar-like structure. Surface and Interface Analysis, 2015, 47, 45–55.

4. Cole, M., Lindeque, P., Halsband, C., & Galloway, T.S. Microplastics as contaminants in the marine environment: a review. Marine Pollution Bulletin, 2011, 62, 2588–2597.

5. El-Saftawy, A.A., Elfalaky, A., Ragheb, M.S., & Zakhary, S.G. Electron beam induced surface modifications of PET film. Radiation Physics and Chemistry, 2014, 102, 96–102.

6. Erni-Cassola, G., Gibson, M.I., Thompson, R.C., & Christie-Oleza, J.A. Lost, but found with Nile red: a novel method for detecting and quantifying small microplastics in environmental samples. Environmental Science and Technology, 2017, 51, 13641–13648.

7. Galloway, T.S., & Lewis, C.N. Marine microplastics spell big problems for future generations. Proceedings of the National Academy of Sciences, 2016, 113, 2331–2333.

8. GOI. Annual report 2016–17, Salt Department, Ministry of Commerce and Industry, Government of

India, 2017.

9. Hou, L., Xi, J., Liu, J., Wang, P., Xu, T., Liu, T., Qu, W., & Lin, Y.B. Biodegradability of polyethylene mulching film by two Pseudomonas bacteria and their potential degradation mechanism. Chemosphere, 2022, 286, 131758.

10. Ibor, O.R., Mpama, N.O., Okoli, C.P., Ogarekpe, D.M., Edet, U.O., Ajang, R.O., Onyezobi, C.E., Anyanti, J., Idogho, O., Aizobu, D., & Arukwe, A. Occurrence, identification and characterization of plastic pollution from an open solid waste dumpsite in Calabar, Southern Nigeria. Environmental Advances, 2023, 11, 100338.

11. Ivleva, N.P. Chemical analysis of microplastics and nanoplastics: challenges, advanced methods, and perspectives. Chemical Reviews, 2021, 121, 11886–11936.

12. Lee, H.-J., Song, N.-S., Kim, J.-S., & Kim, S.-K. Variation and uncertainty of microplastics in commercial table salts: critical review and validation. Journal of Hazardous Materials, 2021, 402, 123743.

13. Mozaffarian, D., Fahimi, S., Singh, G.M., Micha, R., Khatibzadeh, S., Engell, R.E., Lim, S., Danaei, G., Ezzati, M., & Powles, J. Global sodium consumption and death from cardiovascular causes. New England Journal of Medicine, 2014, 371, 624–634.

14. Park, S.Y., & Kim, C.G. Biodegradation of micro-polyethylene particles by bacterial colonization of a mixed microbial consortium isolated from a landfill site. Chemosphere, 2019, 222, 527–533.

15. Shafea, L., Felde, V.J.M.N.L., Woche, S.K., Bachmann, J., & Peth, S. Microplastics effects on wettability, pore sizes and saturated hydraulic conductivity of a loess topsoil. Geoderma, 2023, 437, 116566.

16. Sorolla-Rosario, D., Llorca-Porcel, J., Pérez-Martínez, M., Lozano-Castelló, D., & Bueno-López, A. Study of microplastics with semicrystalline and amorphous structure identification by TGA and DSC. Journal of Environmental Chemical Engineering, 2022, 10, 106886.

17. Taghavi, N., Udugama, I.A., Zhuang, W.Q., & Baroutian, S. Challenges in biodegradation of non-degradable thermoplastic waste: from environmental impact to operational readiness. Biotechnology Advances, 2021, 49, 107731.

18. Urbanek, A.K., Rymowicz, W., Strzelecki, M.C., Kociuba, W., Franczak, L., & Mironczuk, A.M. Isolation and characterization of Arctic microorganisms decomposing bioplastics. AMB Express, 2017, 7, 148.

19. Urbanek, A.K., Strzelecki, M.C., & Mironczuk, A.M. The potential of cold-adapted microorganisms for biodegradation of bioplastics. Waste Management, 2021, 119, 72–81.

20. Wei, R., Tiso, T., Bertling, J., O'Connor, K., Blank, L.M., & Bornscheuer, U.T. Possibilities and limitations of biotechnological plastic degradation and recycling. Nature Catalysis, 2020, 3, 867–871.

21. Xiang, P., Zhang, Y., Zhang, T., Wu, Q., Zhao, C., & Li, Q. A novel bacterial combination for efficient degradation of polystyrene microplastics. Journal of Hazardous Materials, 2023, 458, 131856.