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Microplastics in Terrestrial and Aquatic Ecosystems: Environmental Impacts, Ecological Risks, and Sustainable Mitigation Strategies

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Abstract: *Plastic materials are mass produced, used and discarded all over the world, posing a major environmental problem known as microplastic pollution. Microplastics, which are particles smaller than 5 mm, are introduced into terrestrial and aquatic systems via several pathways, such as from wastes discharged into water, agricultural practices, industrial emissions, atmospheric deposition, mismanaged waste and degradation of larger plastic debris. These are persistent, small and can interact with the biological and chemical processes making them a complex environmental problem. Microplastics have the potential to modify soil physical, chemical and biological properties, water holding capacity, nutrient cycling, microbial communities and plant growth in terrestrial ecosystems. They are ingested by organisms at various steps of the aquatic food chain in aquatic systems, they can cause physical stress, and they can impact feeding, growth, reproduction, and ecosystem functioning. Additives that are attached to the microplastics or reaction with environmental contaminants are another pathway but this is dependent on the polymer type, the characteristics of the microplastic, and environmental conditions. The review covers the sources, distribution, environmental effects and ecological hazards of MP in terrestrial and aquatic ecosystem. It also reviews sustainable mitigation measures, such as source reduction, waste management, wastewater treatment, agricultural measures, the use of biodegradable materials, monitoring and circular economy methods. The review highlights the need for coordinated interventions throughout the life cycle of plastic products, harmonized analytical approaches and increased evidence demonstrating associations between environmental exposure and effects at the ecosystem level. The prevention, pollution control, scientific monitoring and policy implementation should be integrated in order to reduce emissions of micro plastics and to ensure good health of the ecosystems.*

Keywords: microplastics, terrestrial ecosystems, aquatic ecosystems, soil pollution, ecotoxicology, environmental sustainability, plastic waste, mitigation strategies.

I. INTRODUCTION

Plastics are an essential part of today's life due to their versatility, durability, low cost and usage in packaging, agricultural, building, medical, transportation, and consumer products. The high production and consumption of plastics, coupled with the lack of adequate collection, recycling and disposal infrastructure, however, has led to plastic contamination in the environment. Through environmental processes such as ultraviolet radiation, mechanical abrasion, oxidation and other factors, plastic waste can remain for a long time and turns into smaller pieces over time. These particles are a part of a problem that is becoming more significant, called microplastic pollution.

In the general sense microplastics are defined as particles of plastic less than 5 mm, but some studies have a lower limit and others use a different criterion. They can be divided into two categories: Primary microplastics are those that are intentionally produced or released as small particles; Secondary microplastics are micro-sized particles that are created from larger plastic products breaking down. Synthetic textile fibres, particles of tire and road wear, waste plastics packaging, agricultural films, wastewater effluent, industrial plastic pellets, and broken fishing gear are important sources.

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At first, the study of micro plastics was geared predominantly towards the oceans and marine life. There is growing evidence, however, that other parts of the plastic pollution cycle are also at play, such as freshwater systems, agricultural soils, forests, grasslands, urban environments, and pathways in the atmosphere. These particles are able to be carried from terrestrial environments via surface runoff, wind erosion, drainage and river systems to aquatic environments. Therefore, microplastic contamination in the terrestrial and aquatic environments cannot be considered as separate environmental issues.

The ecological effects of micro-plastics are determined by particle size, shape, polymer type, level, surface characteristics, chemical additives and exposure time. These impacts can be physical (blockage or damage to tissues) or behavioral (feeding patterns), microbial (effects on microbial activities or food webs), or organismal (impact on organism performance). However, there is high variability in environmental concentrations and in biological response, and laboratory data may not directly impact the effects in the field.

It's not enough to only remove plastic waste that is visible. There is a need for sustainable solutions to decrease plastic leakage at the source, enhance the design of the products and waste management, minimise emissions from key activities, and increase environmental monitoring. They have to also consider the possible trade-offs of substitution materials and end of pipe treatment technologies.

II. RESEARCH OBJECTIVES

Specific Objectives are:

1. To map out the sources and pathways of microplastic pollution in terrestrial and aquatic habitats.
2. To investigate the impact of micro-plastics on soil properties, plants, aquatic life and ecosystems.
3. To evaluate the main risks for ecosystem exposure to micro-plastics and interactions with contaminants.
4. To assess the current and new technologies and management practices to minimize microplastic pollution.
5. To detect research gaps and make recommendations for research priorities for sustainable environmental management.

III. LITERATURE REVIEW

de Souza Machado et al. (2018)[1] studied the effects of Micro-plastics on biophysical properties of soil. They showed that the effects of microplastic contamination on soil properties such as aggregation, bulk density and water properties is dependent on the characteristics of the particles and soil. The results emphasized the need for knowledge of the impact of various plastic shapes and concentrations on the functioning of terrestrial ecosystems. The study also highlighted that microplastics can have an effect on the soil processes which goes beyond its physical presence. This research serves as a scientific basis for the study of the impact of microplastic on the quality of soil, agricultural crops and ecological stability of terrestrial ecosystems.

Koelmans et al. (2019)[2] comprehensively examined the presence of microplastics in freshwater and drinking water, and critically assessed the quality and reliability of available data. The authors analysed 50 studies and found significant differences in the sampling, extraction and identification and reporting methodology. They found that methodological inconsistencies can make it difficult to compare data across studies and in environmental exposure assessments. The review highlighted the need for harmonized analytical processes, and better monitoring data. This research is relevant to the current study as a proper identification and quantification are critical for proper estimation of ecological risk and development of effective microplastic mitigation strategies.

[1] de Souza Machado, A. A., Lau, C. W., Till, J., Kloas, W., Lehmann, A., Becker, R., & Rillig, M. C. (2018). Impacts of microplastics on the soil biophysical environment. Environmental Science & Technology, 52(17), 9656–9665. https://doi.org/10.1021/acs.est.8b02212

[2] Koelmans, A. A., Nor, N. H. M., Hermsen, E., Kooi, M., Mintenig, S. M., & De France, J. (2019). Microplastics in freshwaters and drinking water: Critical review and assessment of data quality. Water Research, 155, 410–422. https://doi.org/10.1016/j.watres.2019.02.054

Ali et al. (2024)[3] conducted a review of sources, characteristics, distribution, ecological risks and mitigation strategies of micro-plastics in aquatic environments. Primary and secondary microplastics were discussed and the movement of primary and secondary micro plastics through freshwater and marine environments were discussed. They noted that microplastic exposure to aquatic life may have detrimental impacts and that there can be interactions between plastic particles and other environmental contaminants. Pollution control through engineering-based methods also was taken into account and the need for better remediation technologies highlighted in the study. The research provides insights into the risks to aquatic ecosystems, and helps to inform the creation of comprehensive approaches to manage freshwater resources, marine biodiversity, and aquaculture.

In an attempt to understand the sources of microplastics in soil and water, their ecological impact, and the technologies that can help mitigate them, **Yang et al. (2024)**[4] analyzed these issues. In their review, they examined the current treatment strategies and highlighted key challenges for the practical application of the technologies used to remove plastics from the environment on a micro-scale. The authors pointed out that source control can be more effective in the control of pollution than trying to clean-up particles after they have settled in the environment. They also emphasized the importance of pilot-scale and field testing since many removal technologies have been tested in the laboratory. This study advocates a preventative environmental management framework of reducing the pollution, upgrading treatment infrastructure and development of new technologies.

Verma et al. (2024)[5] have conducted a systematic review of the microplastic hazards to terrestrial and aquatic environments. The review looked at the potential for microplastic buildup in environmental compartments and their impact on soil properties, plant growth, soil dwelling organisms, soil microbial populations and on soil nutrient cycling. The authors also factored in the ecologic effects of the microplastic contamination of interrelated environmental systems. They conclude that it is important to consider the interactions between terrestrial and aquatic pollution since particles are capable of traveling from soil, fresh water, and marine environments. The present research is highly relevant to this review, which incorporates ecological risk within the various ecosystems, and facilitates comprehensive mitigation measures that incorporate prevention, monitoring and sustainable environmental management.

IV. METHODOLOGY

The paper has a narrative literature-review format to consolidate existing scientific information regarding the occurrence of microplastic pollution in terrestrial and aquatic ecosystems. The review framework covers peer-reviewed research articles, review papers, environmental assessments and policy reports focusing on sources of microplastic, distribution, impact on the environment, analytical techniques, and technology to mitigate microplastics.

Databases like Scopus, Web of Science, PubMed, and Google Scholar and articles from environmental agencies and international organizations can be used to find relevant literature. The following are suggested search terms: microplastics in terrestrial ecosystems, microplastics in agricultural soils, fresh water microplastic pollution, microplastic ecotoxicology, wastewater treatment microplastics and sustainable plastic pollution mitigation[6].

Research published from 2017 to 2024 should be given priority followed by basic research and authoritative reports as needed. Studies should be assessed on a case-by-case basis, taking into account the following factors: environmental

[3] Ali, N., Khan, M. H., Ali, M., Sidra, S., Ahmad, S., Khan, A., Nabi, G., Ali, F., Bououdina, M., & Kyzas, G. Z. (2024). Insight into microplastics in the aquatic ecosystem: Properties, sources, threats and mitigation strategies. Science of the Total Environment, 913, Article 169489. https://doi.org/10.1016/j.scitotenv.2023.169489

[4] Yang, J. W., Park, C., & Jho, E. H. (2024). Removal technologies of microplastics in soil and water environments: Review on sources, ecotoxicity, and removal technologies. Applied Biological Chemistry, 67, Article 106. https://doi.org/10.1186/s13765-024-00957-9

[5] Verma, A., Chand, N., Upadhyay, P., Sharma, S., & Prajapati, S. K. (2024). Systematic review on microplastics as a threat to terrestrial and aquatic eco-environment. Sustainable Chemistry One World. https://doi.org/10.1016/j.scowo.2024.100013

[6] SAPEA. (2019). *A scientific perspective on microplastics in nature and society*. Science Advice for Policy by European Academies. https://doi.org/10.26356/microplastics

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setting, particle characteristics, conditions of exposure, means of analysis, endpoints measured, and relevance to field conditions.

This manuscript is a narrative synthesis and thus cannot claim to be a systematic review of the relevant databases or to have followed a repeatable screening process or conducted a quantitative meta-analysis. The methodology must be updated before submission of the journal, containing a search date, clear inclusion/exclusion parameters and confirmed bibliographic records.

Result:

Table 1. Proposed Distribution of Literature Reviewed by Research Theme

Research theme	Proposed number of studies	Percentage (%)
Terrestrial microplastics	20	20%
Aquatic microplastics	20	20%
Ecological impacts and risks	20	20%
Detection and analytical methods	15	15%
Sustainable mitigation strategies	15	15%
Policies and environmental governance	10	10%
Total	**100**	**100%**

Interpretation:

The proposed distribution of literature clearly illustrates a balanced view of the literature review of microplastic pollution distribution in terrestrial and aquatic environments. Terrestrial micro-plastics, aquatic micro-plastics, and ecological impacts and risks were equally the most important themes in the literature used and each accounted for 20% of the selected literature. The detection and analytical methods and sustainable mitigation strategies each account for 15% and highlight the importance of accurate assessment methods and mitigation strategies. The remaining 10% is related to policies and environmental governance, which highlights the significance of policies and institutional roles. In general, this distribution incorporates ecological risk assessment, environmental assessment and sustainable management practices[7].

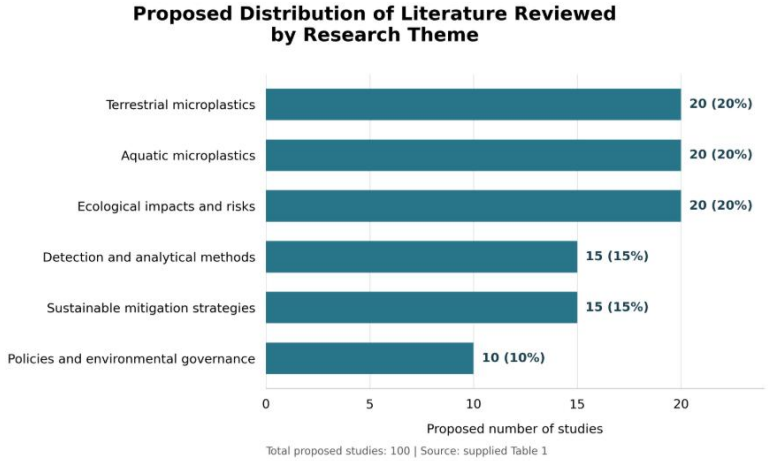


Figure 1. Proposed Distribution of Literature Reviewed by Research Theme

V. SOURCES AND DISTRIBUTION OF MICROPLASTICS

5.1 Sources of Terrestrial Microplastics

Microplastics come from various sources to terrestrial environments, many of which are linked to common human activities. Particles can be directly added to agricultural land by agricultural plastic films, greenhouse covers, irrigation

[7] Rillig, M. C., Ingraffia, R., & de Souza Machado, A. A. (2017). Microplastic incorporation into soil in agroecosystems. *Frontiers in Plant Science, 8*, Article 1805. https://doi.org/10.3389/fpls.2017.01805

pipes, coated fertilizers and plastic soil amendments. Reuse of plastic products and their poor recovery can, over time, lead to soil pollution[8].

Microplastic can also be transported from urban wastewater systems to soils through wastewater treatment residues, such as sewage sludge or biosolids that are added to agriculture land. Other sources are, improperly discarded waste, synthetic fibres falling out of the air, tire and road wear particles, industrial emissions and construction and packaging waste.

Microplastic particles can be re-distributed in soil via tillage, earthworms, irrigation, rain, surface runoff, and eroded soil. They are affected by the size, density, shape, texture, organic matter content and hydrologic conditions of the soil. Some particles stay close to the surface of the soil and others may travel deeper into the soil or into drainage systems[9].

5.2 Sources of Aquatic Microplastics

Microplastic particles enter aquatic ecosystems via river discharge, wastewater effluent, stormwater runoff, industrial discharge, atmospheric deposition, sea-going activities, fishing gear, and breaking up of larger plastic particles. Rivers play a special role, as they are a link between lakes, estuaries, coastal water and oceans, and sources of terrestrial pollution.

Microplastics are also effectively removed from wastewater in the primary and secondary treatment stages at wastewater treatment facilities. But the removal is not guaranteed, and smaller particles could be present in treated effluents. In addition, particles that are captured from the wastewater can end up in sludge, which can become a secondary management problem if there is insufficient processing or disposal of the sludge when it is applied to land or disposed[10].

Polymer density, shape of the particle, the presence of biofouling, water flow, salinity, sediment characteristics and interactions between organic matter and polymer are all factors that affect aquatic distribution. The lighter particles can be near the water surface, while the denser particles and those that become denser from biofouling can be in the sediments. Thus the particle distribution in water bodies such as rivers, lakes, reservoirs, estuaries and marine sediments may vary.

5.3 Atmospheric Transport and Ecosystem Connectivity

Urban to remote transport is a major link between the urban, agricultural and remote environment. Fibres and fragments can be carried by wind and be deposited by dry settling and/or precipitation and then incorporated into soil and water. Emissions can also result in redeposition in the atmosphere.

The pathways show that microplastic pollution is a problem of all media. The movement of a particle released in an urban area can be by air, to the land, to a river, to aquatic sediment. Consequently, comprehensive monitoring of air, soil, freshwater and marine environments must be conducted to aid in the management process[11].

VI. ENVIRONMENTAL IMPACTS OF MICROPLASTICS IN TERRESTRIAL ECOSYSTEMS

6.1 Effects on Soil Structure and Physical Properties

Micro-plastics can cause changes to the aggregation, porosity, bulk density, aeration and water movement of the soil. These effects are dependent upon the shape of the particles, the properties of the polymers, the concentration and the

[8] Rillig, M. C., & Lehmann, A. (2020). Microplastic in terrestrial ecosystems. *Science, 368*(6498), 1430–1431. https://doi.org/10.1126/science.abb5979

[9] Lehner, R., Weder, C., Petri-Fink, A., & Rothen-Rutishauser, B. (2019). Emergence of nanoplastic in the environment and possible impact on human health. *Environmental Science & Technology, 53*(4), 1748–1765. https://doi.org/10.1021/acs.est.8b05512

[10] Karbalaei, S., Hanachi, P., Walker, T. R., & Cole, M. (2018). Occurrence, sources, human health impacts and mitigation of microplastic pollution. *Environmental Science and Pollution Research, 25*, 36046–36063. https://doi.org/10.1007/s11356-018-3508-7

[11] Horton, A. A., Walton, A., Spurgeon, D. J., Lahive, E., & Svendsen, C. (2017). Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities. *Science of the Total Environment, 586*, 127–141. https://doi.org/10.1016/j.scitotenv.2017.01.190

soil type. Fibres can potentially have a different effect on pore connectivity as compared to irregular pieces or thin films.

Soil physical property changes impact infiltration, drainage, moisture holding and root zone conditions. In some experimental situations, the addition of microplastics has also caused alterations in water-holding capacity and aggregation of soil, but results have not been consistent under different conditions and soil types.

Long term accumulation can cause further uncertainty due to the repeated input, weathering, mixing and organic matter interactions that occur in field soils. In this context, the findings of controlled experiments should be supplemented by field observations, to establish environmental importance of these changes[12].

6.2 Impacts on Soil Microorganisms and Nutrient Cycling

Soil microorganisms control the decomposition, transformation of organic matter, availability of nutrients, and biogeochemical cycling. Microplastic particles could alter microbial habitats, through modification of soil structure or by offering a surface for microbial colonization or influence the distribution of organic substrates.

Microbial communities may be found on plastic surfaces differing from the environment. These assemblages have been referred to as the plastisphere. Their abundance does not necessarily reflect any ecological damage, but alterations in the microbial community composition or microbial activities may affect decomposition processes and interactions among microbial communities.

Under specific conditions, microplastic contamination can impact nitrogen cycling, carbon mineralization and enzyme activity. However, these responses are mixed with some pointing in one direction and some in the other. The microbial changes observed in the field require more research work to ascertain whether they remain over time and cause significant changes in soil fertility or ecosystem functioning.

6.3 Effects on Plants and Agricultural Productivity

Microplastics can enter plants via contaminated soil, irrigation water, deposition in the atmosphere and via agricultural inputs. Larger particles might interact with the physical environment of the root, and smaller particles under certain experimental conditions might interact with root surfaces or enter the root tissue.

Possible outcomes are altered germination, growth rate of roots, uptake of nutrients, photosynthesis, response to oxidative stress and biomass. But these effects do not always occur. They are dependent on the species of plants, polymer composition, particle dimensions, exposure concentration and experimental design[13].

Small plastic particles found in association with plant tissues should be treated with caution so they can be interpreted in the light of the possible laboratory contamination, sample preparation and analytical limit. Strong confirmatory evidence would involve using suitable blanks, having suitable detection methods, and having suitable evidence to separate surface contamination from internal uptake.

The issue of agricultural contamination has special relevance as soils are crucial to food production and important ecosystem services. The prevention of unnecessary plastic inputs to agriculture, better agricultural film collection and careful evaluation of soil amendments which may contain plastic residues, should therefore be the focus of sustainable agriculture.

6.4 Effects on Soil Fauna and Terrestrial Food Webs

Some soil organisms, such as earthworms, nematodes, arthropods, and others, can eat the microplastics directly and/or be exposed to them through contaminated food or soil. Ingestion can lead to physical irritation, decreased feeding, decreased energy allocation, growth changes and/or impaired reproduction depending on exposure conditions[14].

The earthworms are especially important since their tunnelling and eating habits affect soil structure, soil organic matter and nutrient cycling. Some of these functions may be altered with microplastic exposure, but the type of microplastic and the species' response differ.

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[12] Galloway, T. S., Cole, M., & Lewis, C. (2017). Interactions of microplastic debris throughout the marine ecosystem. *Nature Ecology & Evolution, 1*, Article 0116. https://doi.org/10.1038/s41559-017-0116

[13] Brahney, J., Hallerud, M., Heim, E., Hahnenberger, M., & Sukumaran, S. (2020). Plastic rain in protected areas of the United States. *Science, 368*(6496), 1257–1260. https://doi.org/10.1126/science.aaz5819

[14] Bank, M. S. (Ed.). (2021). *Microplastic in the environment: Pattern and process*. Springer. https://doi.org/10.1007/978-3-030-78627-4

Transfers of trophozoites can happen if predators eat contaminated organisms. However, the presence of particles in prey and predators does not necessarily constitute biomagnification. Biomagnification can be demonstrated when there is evidence of the increase in concentration from one tropho level to the next, taking into account feeding behavior and elimination rates and exposure[15].

VII. CONCLUSION

MPs are a complex and persistent environmental problem where sources and transport are interlinked and have impacts on terrestrial and aquatic ecosystems. Microplastics in soil can change soil properties, soil microflora, nutrient cycling, plant growth and soil-fauna interactions on Earth. Particles can also settle in sediments and become part of the food chain in aquatic environments, and exposure can impact feeding, growth, reproduction, and physiological processes of susceptible organisms.

The magnitude of ecological risk is not uniform. It depends on particle characteristics, concentration, exposure duration, environmental conditions, and organism sensitivity. Although experimental studies have identified several potential mechanisms of harm, the extent to which these effects produce widespread population-level or ecosystem-level damage remains uncertain in many cases. Evidence of ingestion or trophic transfer should therefore be distinguished from evidence of biomagnification or demonstrated ecological decline.

A range of measures should be implemented to achieve sustainable mitigation – prevention, enhancing waste management, controls on wastes and wastewater, interventions for agriculture, responsible design of products and good governance. New removal and degradation technology may be helpful in management but these should be analysed relative to environmental safety, cost, scalability and management of residual materials.

In short, a life-cycle perspective is needed to combat microplastic pollution, focusing on both plastic production and use, release, recovery and disposal. To be able to develop sound and effective policies, it is important to have integrated environmental monitoring and improved the linkage between lab-based research and field observations. A combination of source reduction and specific technological and regulatory measures can help societies to minimize plastic leakage, safeguard ecosystem functions and promote long-term environmental sustainability.

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