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The Chemistry of Micro-Plastics and Nano-Plastics in Soil-Water

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Abstract

Microplastics (MPs) and nanoplastics (NPs) have become ubiquitous contaminants in soil–water systems, posing escalating ecological and human health risks across diverse environments. Their persistence and complex degradation dynamics are increasingly influenced by climate-driven physicochemical processes. This study investigates the role of fluctuations in selected reactive oxygen species (ROS)—specifically hydrogen peroxide (H_2O_2), superoxide radicals (O_2^{-}), hydroxyl radicals (•OH), and peroxyl radicals (ROO•)—on the degradation behaviour of MPs and NPs within soil–water interfaces. The work elucidates how variations in the concentrations and reactivity of these radicals, governed by climate-induced phenomena such as altered precipitation patterns, droughts, heatwaves, and increased wind or storm activity, significantly affect the oxidative degradation pathways of plastic particles. Findings indicate that two principal mechanisms—direct oxidation and indirect oxidation—govern the degradation of MPs and NPs initiated by these reactive radicals. Climate-induced changes in soil moisture, temperature, and redox potential modulate the abundance and activity of ROS, thereby influencing polymer breakdown rates, fragmentation, and the formation of secondary degradation products. Such variations have far-reaching ecological implications, potentially altering contaminant transport, bioavailability, and toxicity in terrestrial and aquatic systems. The study highlights the urgent need for deeper investigation into the mechanistic links between radical-driven degradation processes and the migration, transformation, and ecotoxicity of MPs and NPs under dynamic climatic conditions. A comprehensive understanding of these interactions is essential for developing adaptive environmental protection and remediation strategies aimed at mitigating the growing threat of microplastic and nanoplastic pollution in a changing global climate.

Keywords
Microplastics;
Nanoplastics;
Pathways;
Reaction Kinetics;
Radicals, Soil-Water

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INTRODUCTION

Recent farming techniques and practices have made agroecosystems more exposed to plastic contamination (Henseler et al., 2022; . Hossain et al., 2025; . Huang et al., 2021; Mondol et al., 2025; Eid et al., 2025; Shen et al., 2025). Information and data on the effects and chemistry of hydrogen peroxide, superoxide radicals, hydroxyl and peroxyl radicals in the presence of nanoplastics and microplastics on soil biota are currently limited (Mondol et al., 2025; Jingya et al., 2025; Chen et al., 2024 a and b). With reference to studies and research, these nanoplastics and microplastics are into the agricultural system. It has been documented that greater than 90.0×10^6 polyethylene bags are disposed of as solid waste, non-renewable waste and trash yearly (Mondol et al., 2025; Banerjee et al., 2025b ; Banerjee et al., 2025a).

Packaging is among the sources of the majority of plastic contamination in the public. Plastic resins are constantly becoming prevalent in consumer plastic products. Efforts to maintain, improve or increase soil fertility, fertiliser and soil amendment using processed organic wastes are becoming standard procedures (Mondol et al., 2025 ; Hendawy et al., 2025 ; Tong et al., 2025). Figure 1 shows possible input sources of microplastics into the agroecosystem and the use and polymer type of plastics in agriculture. Figure 2 presents the nanoplastics and microplastics sources in soil agroecosystems. Presently, composts developed from green cuttings and municipal biowaste are selected for soil improvement because the utilisation of sewage sludge as organic fertiliser is limited based on the contents (heavy metals, resistance genes and medicines) that could harm to humans and the ecology (Delibacak et al., 2020; Mondol et al., 2025; Liu et al., 2025a; Ma et al., 2025). It has been reported that plastic loads in composts can reach 1.36 g kg^{-1}, and plastics in form of nanoplastics and microplastics have been discovered in soil that was modified with compost (Braun et al., 2023; Wang, 2025; Zaffar et al., 2025). Figure 3 shows a schematic representation of plastic sources and their behaviour on soils. Figure 4 shows the fate of plastics in the environment. Figure 5 presents the transport of nanoplastics and microplastics from sources to the environment.

Microplastics and nanoplastics are emerging pollutants in recent environmental pollution issues because of their pervasiveness and stability in the environment (Ya et al., 2022; Verla et al., 2019). Microplastics and nanoplastics are frequently found in agricultural soils. There are environmental issues in relation to these two particles, because it is known that these microplastics and nanoplastics can affect the functionality and structure of soil and engineering properties of the soil as well (Yu et al., 2023; Mondol et al., 2025). More data and information on microplastics and nanoplastics, fate, biodegradation and mechanisms in the soil can be established in the literature, such as Verla et al.(2019); Roy et al. (2022); de Souza Machado et al. (2018); Roy et al. (2022) and Ya et al. (2021).

In addition, information and data on the effects, impacts and influence of these particles on normal functions of the human body (the endocrine and immune systems, and the induction of diseases can be established in previous studies such as Sun and Wang (2023); Thompson et al. (2024); Sutkar et al. (2023). Hydrogen peroxide, superoxide radicals, hydroxyl and peroxyl radicals (free radicals) in the environment perform a critical role in the degradation of microplastics and nanoplastics. These free radicals oxidise microplastics and nanoplastics in the soil (Wang et al., 2024a; Zhu et al., 2025; Mondol et al., 2025), while the soil-water system signifies a significant pool for the accumulation, migration, and transformation of microplastics and nanoplastics in the soil. The soil-water system serves as a hotbed for the generation of free radicals, which clutches great significance in explaining the biogeochemical characteristics and behaviours of microplastics and nanoplastics affected by free radicals (Liu et al., 2024a; Tao et al., 2025; Chen et al., 2020; Chia et al., 2022; Chia et al., 2021; Bleasing and Amelung 2018; Bucci et al., 2024; Qiao et al., 2025). These free radicals perform a central role in numerous biological and chemical processes, which indicates that alterations of hydrogen peroxide, superoxide radicals, hydroxyl and peroxyl radicals can be directly associated with matter circulation and energy transformation in the soil-water system (Das, 2023;Xiao et al., 2023; Wang et al., 2020; Wang et al., 2021a; ; 2022a; Nizzeto et al., 2016 Nawab et al., 2024; Lozano et al., 2021a; Arab et al., 2024; Haque and Fan 2023; Estahbanati and Fahrenfeld 2016; . Feng et al., 2022; . Germann, 2020; . Denissen et al., 2022; . Ding et al., 2022c; . Dos Santos et al.,,2023; Zhu et al., 2025; Liu et al., 2025b; Sukharev et al., 2025).

Figure 6 shows an overview of the presence of microplastics and nanoplastics in the soil and plants. Figure 7 presents a summary of microplastics and nanoplastics movement in the soil and plant at various stages. Radicals such as hydrogen peroxide, superoxide radicals, hydroxyl and peroxyl radicals (free radicals) are extremely reactive in soil-water systems, with a particular attention to soil- water-air interface. The dynamic changes of these radicals (hydrogen peroxide, superoxide radicals, hydroxyl and peroxyl radicals) are complex with respect to environmental situations and can be impacted by nanoplastics and microplastics. Studies have been conducted on these radicals but the reaction kinetics, pathways, or transformation end products of microplastic nanoplastics degradation by these radicals in soil-water systems are not well documented. This study provides a brief review on reaction kinetics, pathways, or transformation end products of microplastic nanoplastics degradation.

MATERIALS AND METHODS

In this dynamic and vital study on the dangers of microplastics-nanoplastics in agricultural soils, the evaluation of the literature based on accomplished information on microplastic and nanoplastic particles presence in the soils, the sampling, examination, evaluation and laboratory analysis of microplastic and nanoplastic in soil samples, and the environment utilising various techniques. The essential information and relevant data (figure and numerical values) were collected and extracted from published databases such as Wiley Online Library link (http://onlinelibrary.wiley.com/), Web of Science link (https://webofknowledge.com/), Taylor and Francis Online link (http://www.tandfonline.com/), SpringerLink (http://link.springer.com/), Scopus link (https:// www.scopus.com/), ScienceDirect link (http://www.sciencedirect.com/), Royal Society of Chemistry (RSC) Publishing link (http://pubs.rsc.org) , PubMed link (https://www.pubmed.ncbi. nlm.nih.gov), MDPI link (https://www.mdpi.com/), Magiran link (https://www.magiran.com/), Google Scholar link (https:// scholar.google.com/), Frontiersin link (https://www.frontiersin.org), Elsevier link (https://www.elsevier.com/), and American Chemical Society (ACS) Publications link (http://pubs.acs.org), using the keywords: chemistry of microplastics in soils, chemistry of nanoplastics in soils, chemistry of microplastics - nanoplastics in soils and a bibliometric analysis and a literature review on the chemistry of microplastics - nanoplastics in soils, chemistry of microplastics in water, chemistry of nanoplastics in water, chemistry of microplastics - nanoplastics in water and a bibliometric analysis and a literature review on the chemistry of microplastics - nanoplastics in water, chemistry of microplastics in soil- water, chemistry of nanoplastics in soil- water, chemistry of microplastics - nanoplastics in soil- water and a bibliometric analysis and a literature review on the chemistry of microplastics - nanoplastics in soil- water.

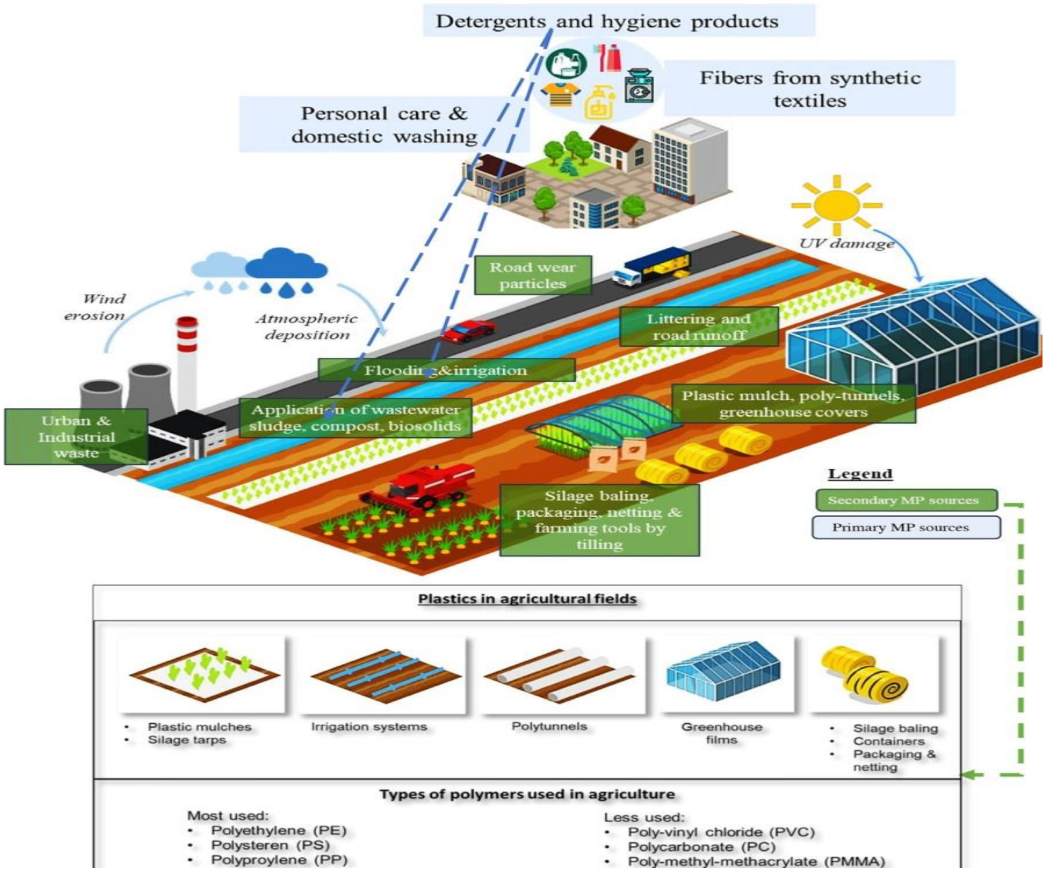


Figure 1: Possible input sources of microplastics into the agroecosystem and the use and polymer type of plastics in agriculture (Source: Shafea et al., 2023).

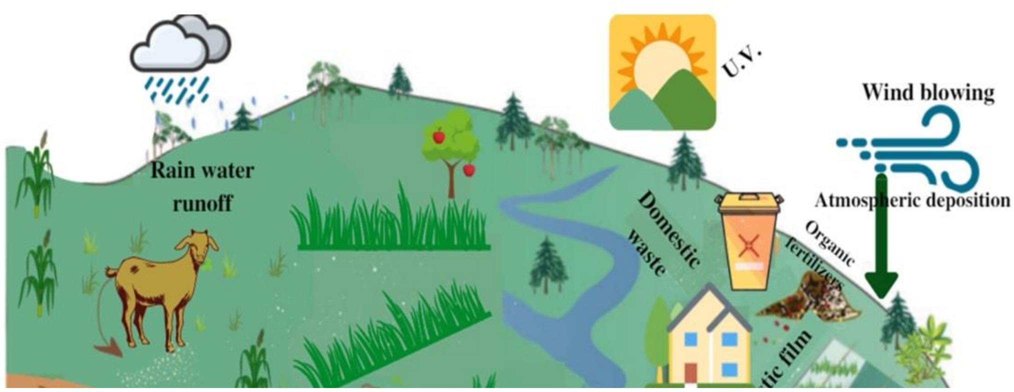
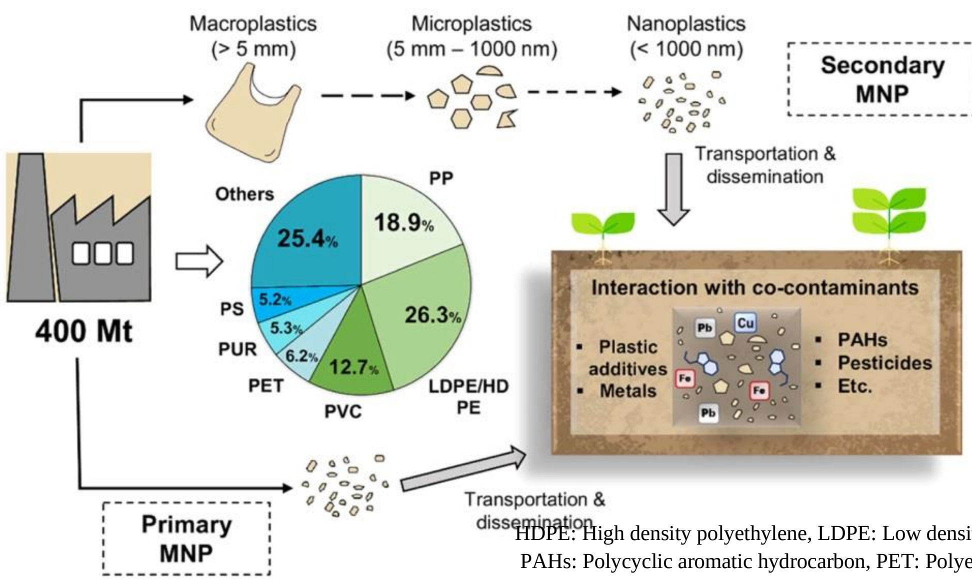


Figure 2: the nanoplastics and microplastics sources in soil agroecosystems (Source: Uwamungu et al., 2022).

Figure 4 The fate of plastics in the environment (Source: Richard et al., 2024).

Figure 3: A schematic representation of plastic sources and their behaviour on soils (Source: Daghighi et al., 2023).



HDPE: High density polyethylene, LDPE: Low density polyethylene, PAHs: Polycyclic aromatic hydrocarbon, PET: Polyethylene terephthalate, PP: polypropylene, PS: Polystyrene, PUR: Polyurethane, PVC: Polyvinyl chloride

Figure 4 The fate of plastics in the environment (Source: Richard et al., 2024).

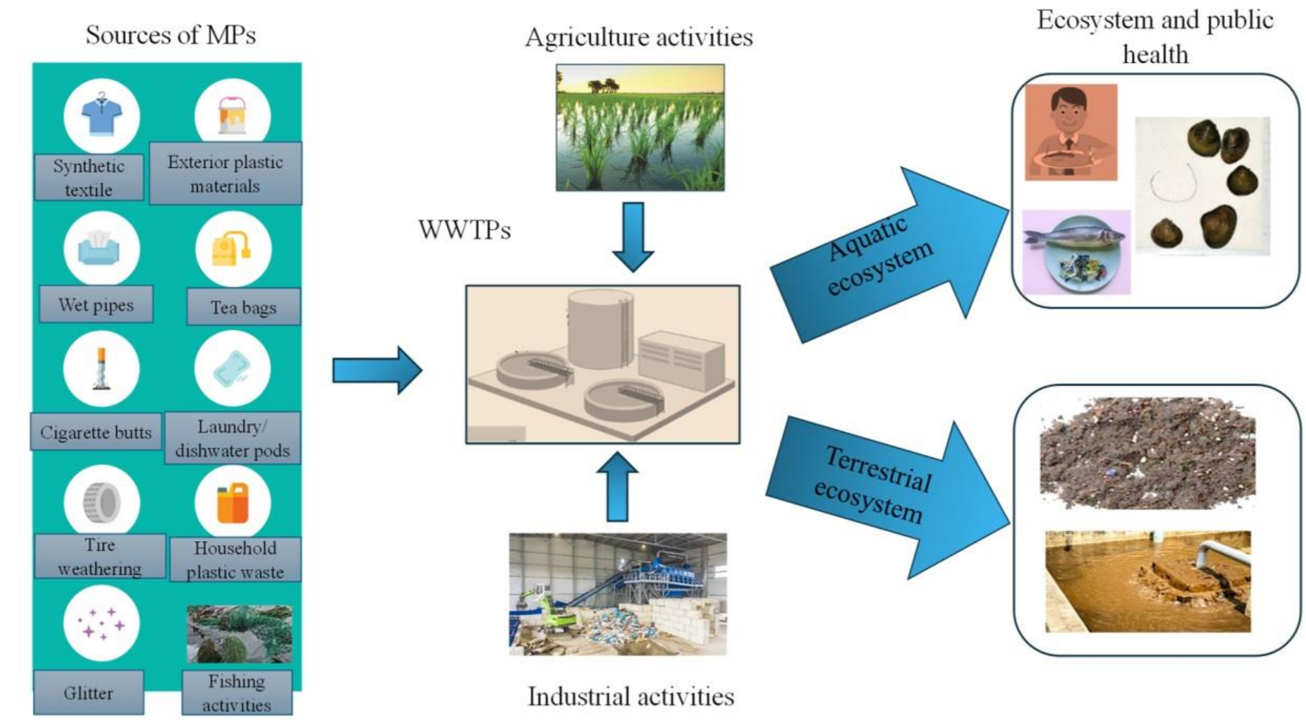


Figure 5 The transport of nanoplastics and microplastics from sources to the environment (Source: Nawab et al., 2023).

Figure 6 An overview of the presence of microplastics and nanoplastics in the soil and plant (Source: Images, 2025)

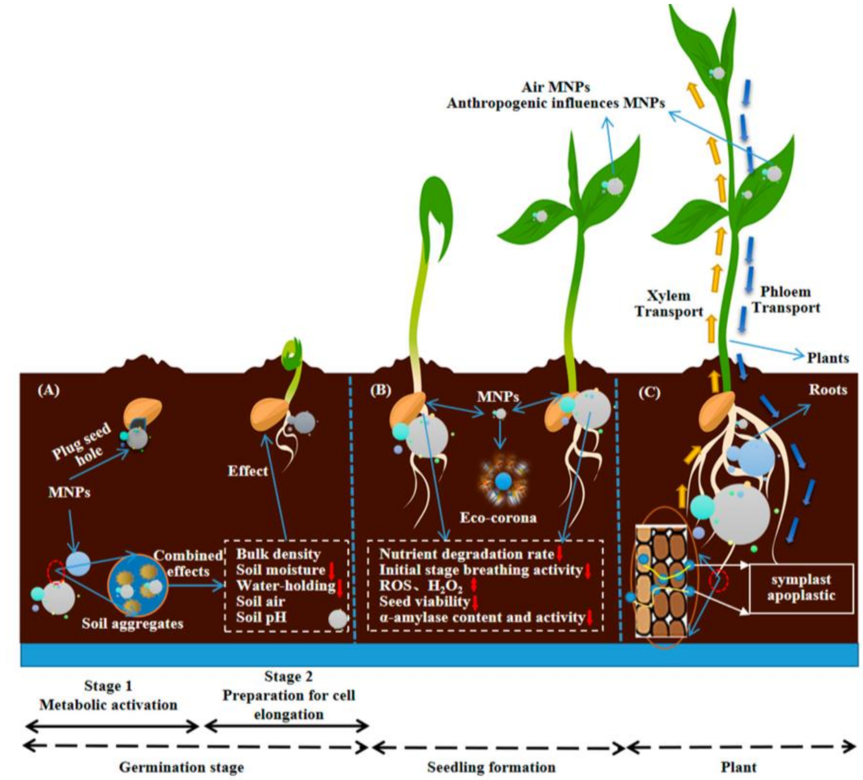


Figure 7: A summary of microplastics and nanoplastics movement in the soil and plant at various stages(Source: Images 2025).

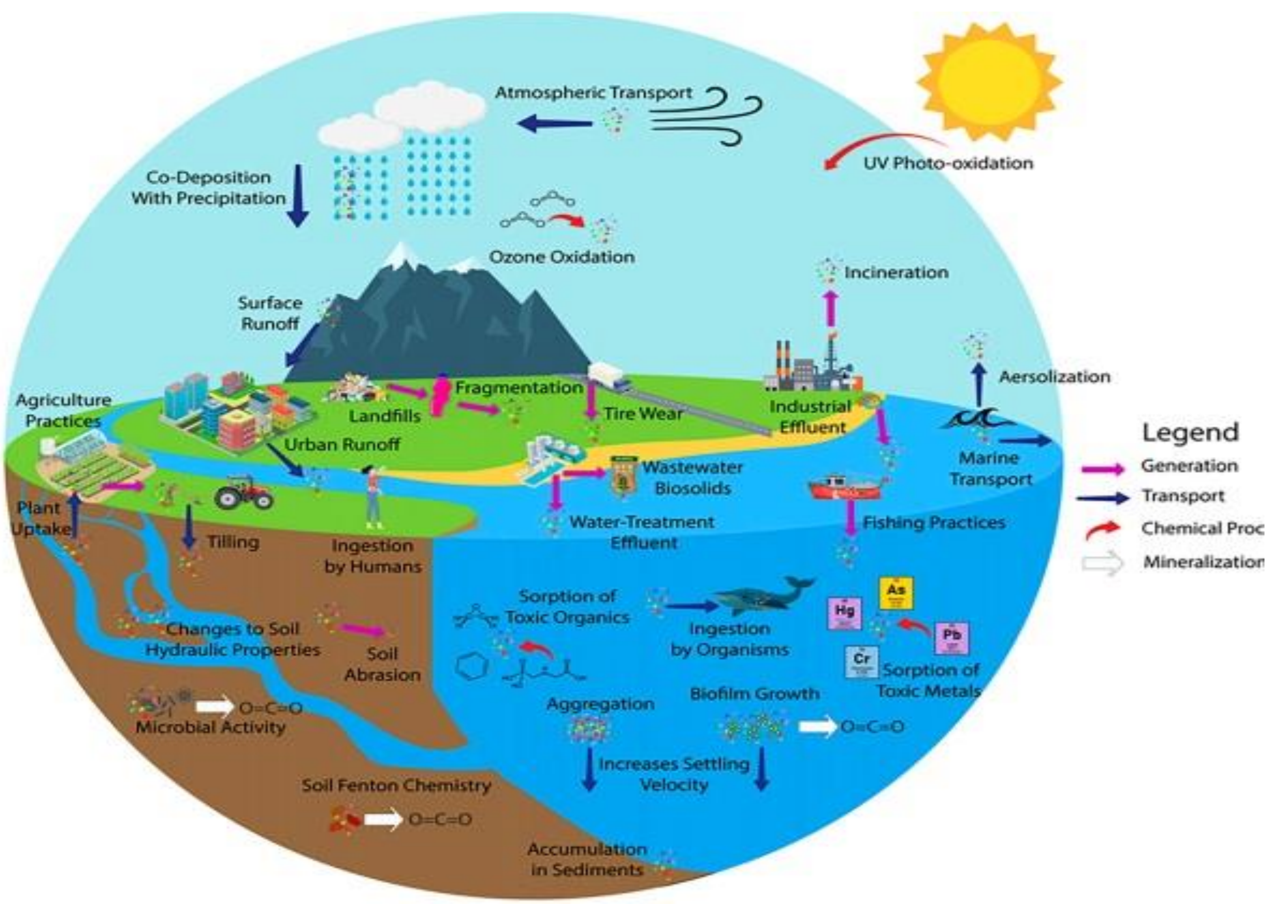


Figure 8: A biogeochemical cycle of microplastics and nanoplastics in the environment including sources of MP generation and

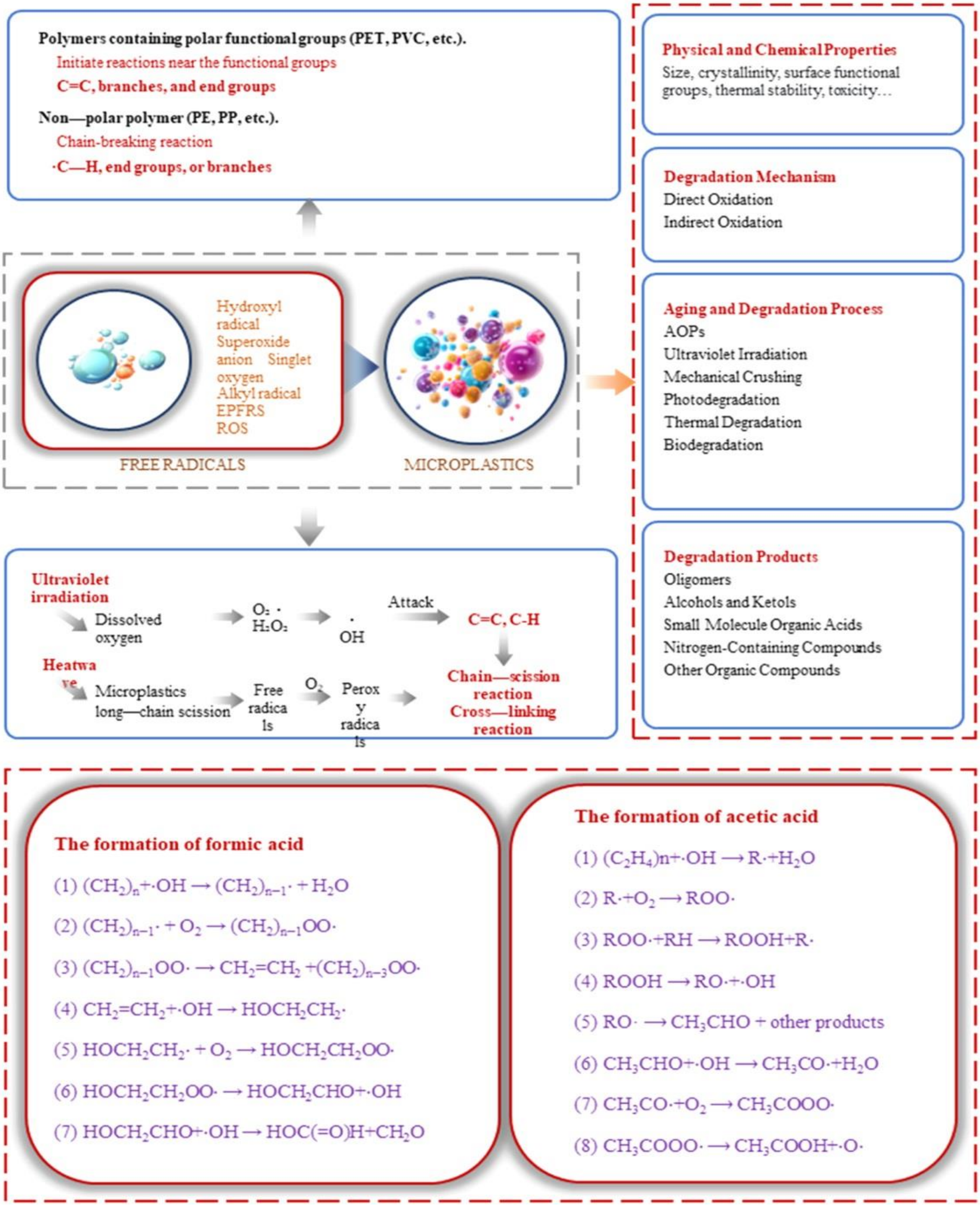


Figure 9 presents mechanism of free radicals initiating the degradation of microplastics and degradation products (Source: Zhu et al., 2025).

Research Findings: Research findings are presented in the following categories:

a) Mechanism of microplastic degradation driven by free Radicals

In soil-water arrangements, free radicals principally attack microplastics and nanoplastics through the oxidation mechanism, resulting in the molecular chains of microplastics and nanoplastics to break or crosslinking, thus changing the chemical and physical properties of the microplastics and nanoplastics. There are two basic mechanisms through which these free radicals start the degradation of microplastics and nanoplastics, which are indirect and direct oxidations. Direct oxidation involves the reaction of free radicals and direct contact with the surface of microplastics and nanoplastics, leading to the breaking down of molecular chains of microplastics and nanoplastics. Indirect oxidation involves Hydrogen peroxide, superoxide radicals, hydroxyl and peroxyl radicals reacting with other molecules on the surface of or within microplastics and nanoplastics, creating new free radicals or active intermediates that can attack the microplastics and nanoplastics (Dong, et al., 2022; Zhao, et al., 2021; Liu, et al., 2022; Xie, et al., 2024a).).

More information on the reaction of free radicals with microplastics and nanoplastics, common products, formation of non-polar and breaking C-H or other weak bonds polymers is established in the literature such as (Li et al., 2022; Shi et al., 2022; Senathiraja, et al., 2023; Wang et al., 2024b; Dogan 2021; Lin et al., 2020; Conradie et al., 2022; Liu et al., 2023; Hu et al., 2022; Biale et al., 2021; Payanthoth et al., 2024;An et al., 2020; .Angelard et al., 2010; .Angon et al., 2023; .Angon et al., 2023; Azeem et al., 2021; . Biale et al., 2021; . Bigalke and Filella 2019; and Golmohammadi et al., 2023). Figure 8 shows biogeochemical cycle of microplastics and nanoplastics in the environment, including sources of microplastics generation and mechanisms for transport, chemical processes, and mineralisation of microplastics and nanoplastics. Figure 9 presents the mechanism of free radicals initiating the degradation of microplastics and degradation products. More on micro- and nanoplastics can be established in the literature such as Monkul and Ozhan (2021); Mortula et al., (2021); Mubin et al., (2023); Nizzetto et al., (2019); Qi et al., (2020); Qian et al., (2018); Qiu et al., (2023); Rassaei , (2023); Rillig et al., (2019); Sadeghi-Kiakhani et al., (2021); Sajjad et al., (2022); Sharma and Mudhoo (2011); Su et al., (2020); Sun et al., (2019); Tan et al., ,(2022); Tang et al., (2021); Townsend et al., (2019); Van Stempvoort et al., (2021); Vethaak and Legler (2021); Hüffer et al. (2018);Hussain et al. (2025); Ingraffia et al. (2022 a and b); Islam et al. (2023); Javier (2023); Karbalaei et al. (2018); Khalid et al. (2020); Kumar et al. (2023) Kumar et al. (2020; 2021); Leifheit et al. (2021);Li et al. (2021); Liu et al. (2017); Liu et al. (2021b); Liu et al. (2021a); Luo et al. (2020); Lwanga et al. (2022); McCormack et al. (2015); Mӧller et al. (2020).

b) Climate change alters the free radicals and affects the fate of Nanoplastics and Microplastics:

Change in precipitation and rainfall pattern, drought, heat-waves and wind speed or storms, which are induced by climate change, always modify soil conditions. These soil modifications incorporate changes in dissolved oxygen levels in soil-water system, frequent shifts in soil microbial communities, variations in the decomposition rate of organic matter, and fluctuations in the leaching process of microplastics, nanoplastics and other pollutants (Johura et al., 2025; Huang et al., 2025; Shabib et al., 2024; Schubert et al., 2025). These subsequent fluctuations, in turn, lead to variations in the generation, transformation, and distribution of these free radicals within soil-water systems. In addition, these variations in free radicals can exert a significant influence and impact on the degradation of microplastics and nanoplastics, thus a significant in the ecological implications. More on modifications in free radical concentrations brought about by various climatic changes and environmental situations with their significant influence on the degradation pathways of microplastics, nanoplastics and the formation of degradation products by these radicals can be established in the literature, such as Wang et al., (2022b). Wang et al., (2020c). Wang et al., (2020). Wang et al., (2022c). Wen et al., (2022). Wen et al., (2022d). Wen et al., (2022e). Williams et al., (2025). Wu et al., (2011). Yang et al., (2021). Yang et al., (2021). Yu et al., (2022). Zhang et al., (2019). Zhang et al., (2023).Zhang et al., (2022). Zhang et al., (2020). Zhou et al., (2023). Knight et al. (2024); Duan et al. (2022); Huang et al. (2024); Ding et al. (2023); Zhang et al. (2025); Fan et al. (2023); Tuchyna and Haas (2025); Shah et al. (2024) Kriech and Osborn (2022); Ma et al. (2021); Ma et al. (2024a); Xu et al. (2023); Xing et al. (2022); Sun et al. (2020); Cheng et al. (2024); Bai et al. (2022); Liu et al. (2024b); Yao et al. (2022); .Xing et al. (2024); Jiang et al. (2023)r; Feld-Cook et al. (2017); Ma et al. (2024b); Ge et al. (2023); Shi et al. (2024); Chen et al. (2024); Cai et al. (2023); Bacha et al. (2024); Han et al. (2024).; Koutnik et al. (2021); Liu et al. (2019); Ding et al. (2022a); Xiao et al. (2023); Ajith et al. (2020); Sunil et al. (2024); Franzellitti et al. (2019); Xie et al. (2024b); and Arienzo et al. (2021). Figure 10 presents free radical generation in soil-water systems under the influence of precipitation anomalies and heat waves caused by climate change.

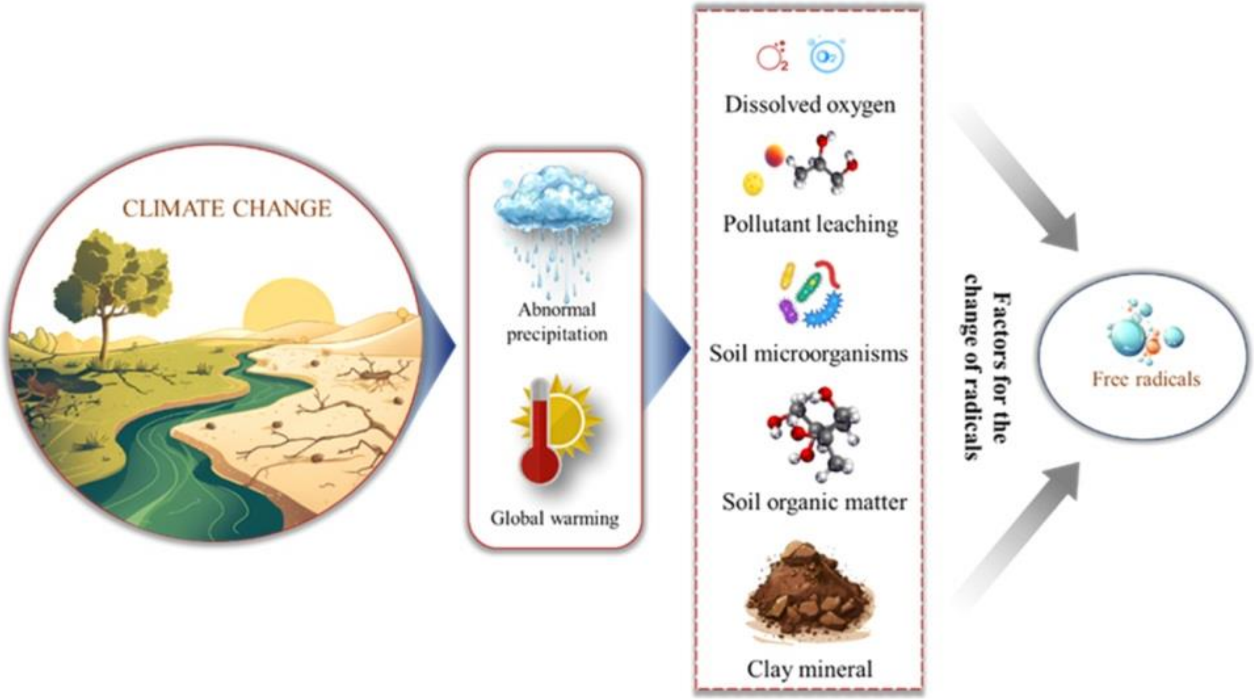


Figure 10: Free radical generation in soil-water systems under the influence of precipitation anomalies and heat waves caused by climate change (Source: Zhu et al., 2025).

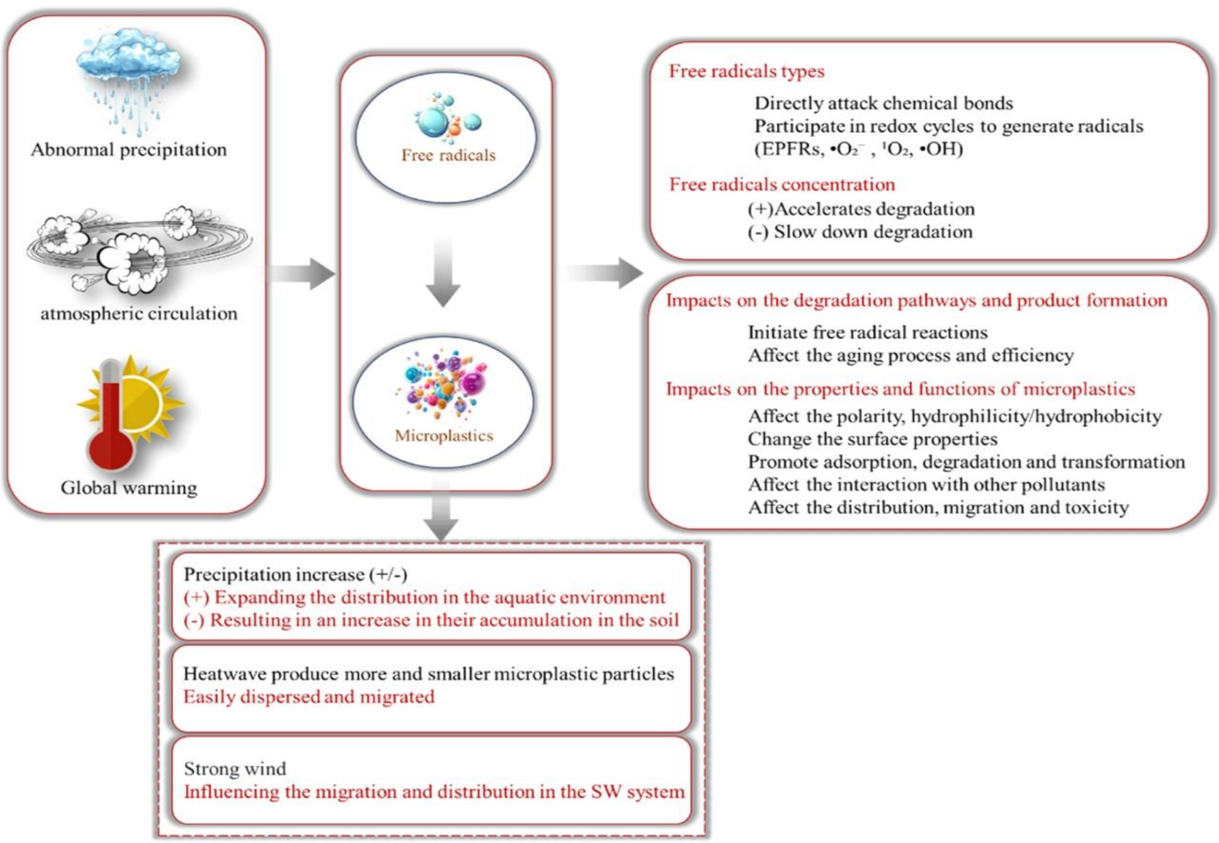


Figure 11: Climate change influences the production of free radicals, subsequently impacting the environmental fate of microplastics (Source: Zhu et al., 2025).

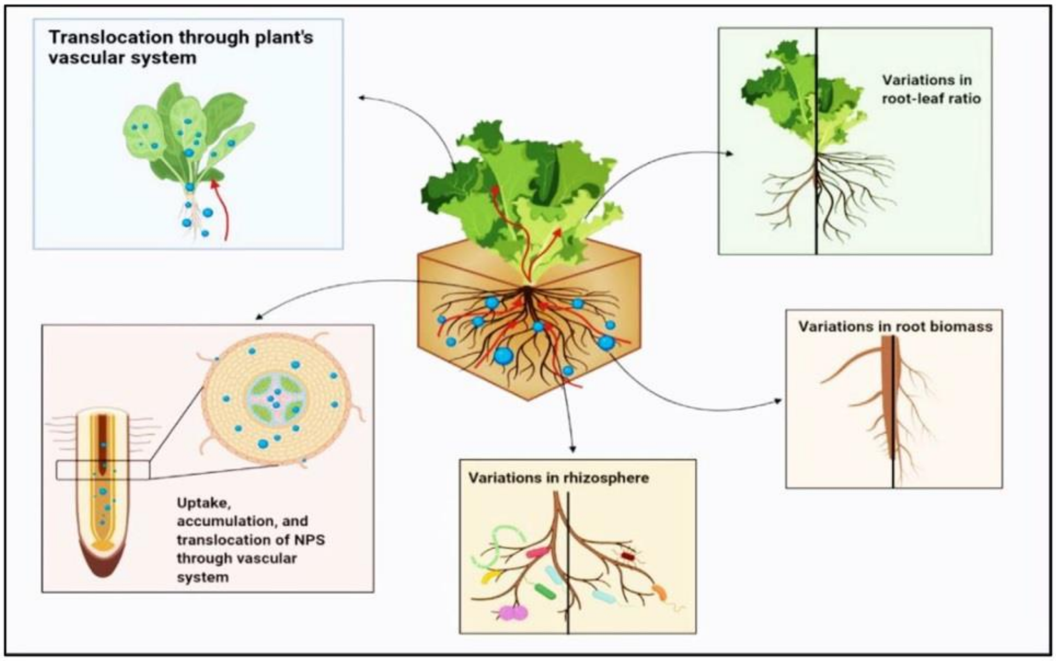


Figure 12: a schematic figure of possible uptake mechanisms and effects on plant growth of microplastics and nanoplastics by plants (Source: Shafea et al., 2023)

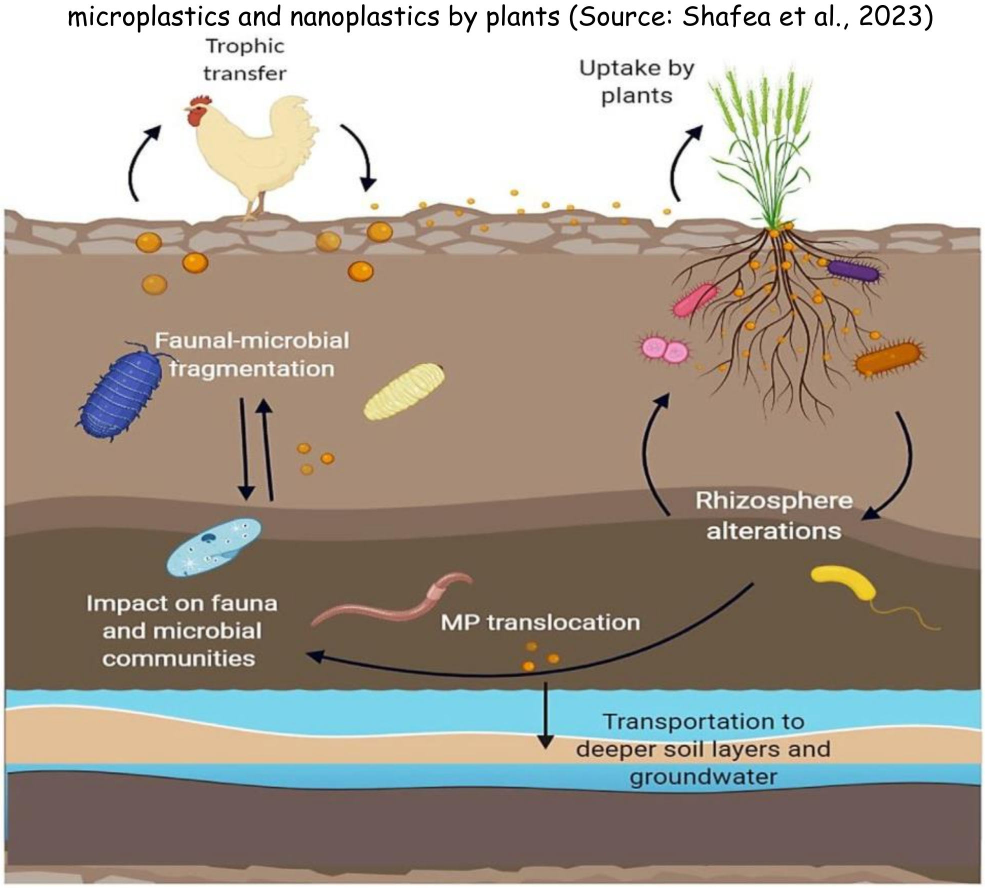


Figure 13: trophic transfer of MPs in soil and groundwater (Source: Shafea et al., 2023)

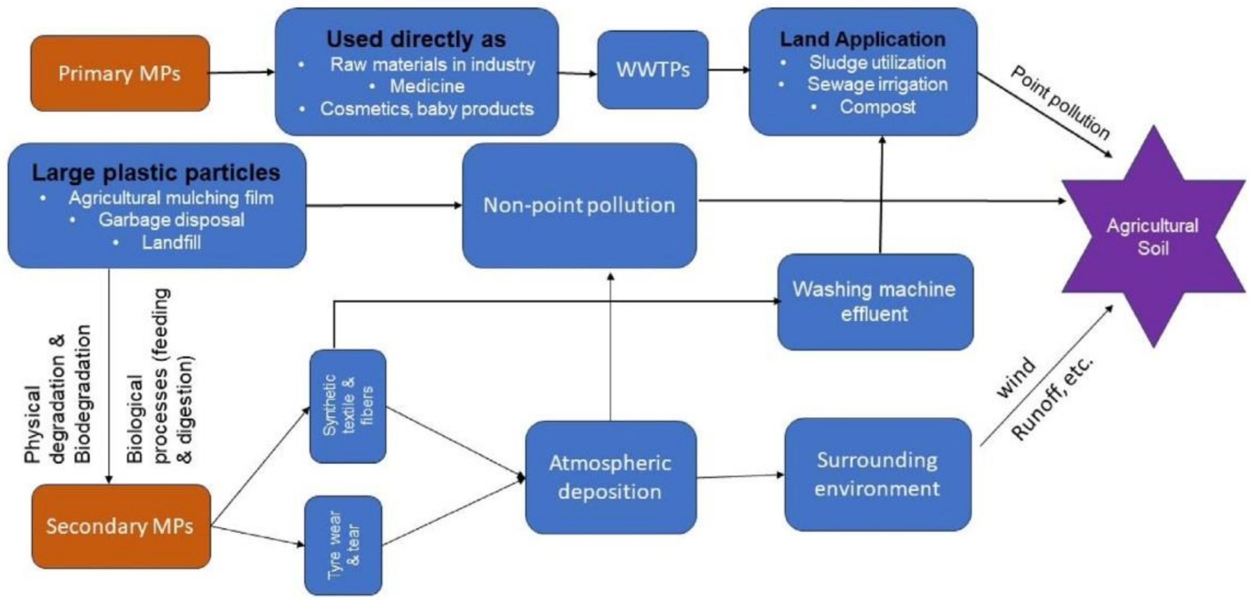


Figure 14: Microplastics and nanoplastics contamination pathway from solid waste to agricultural soil (Source: Mondol et al., 2025).

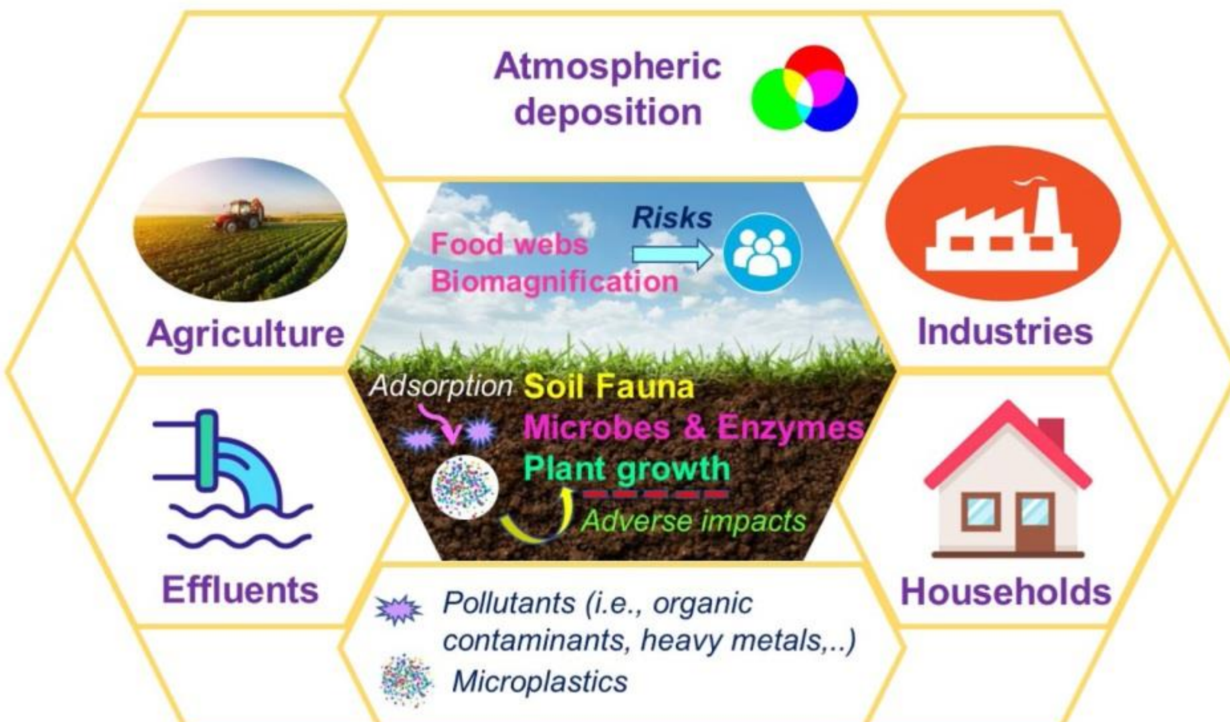


Figure 15: Interactions between microplastics and nanoplastics sources and associated soil organisms as risk pathway.(Source: Nguyen et al., 2025)

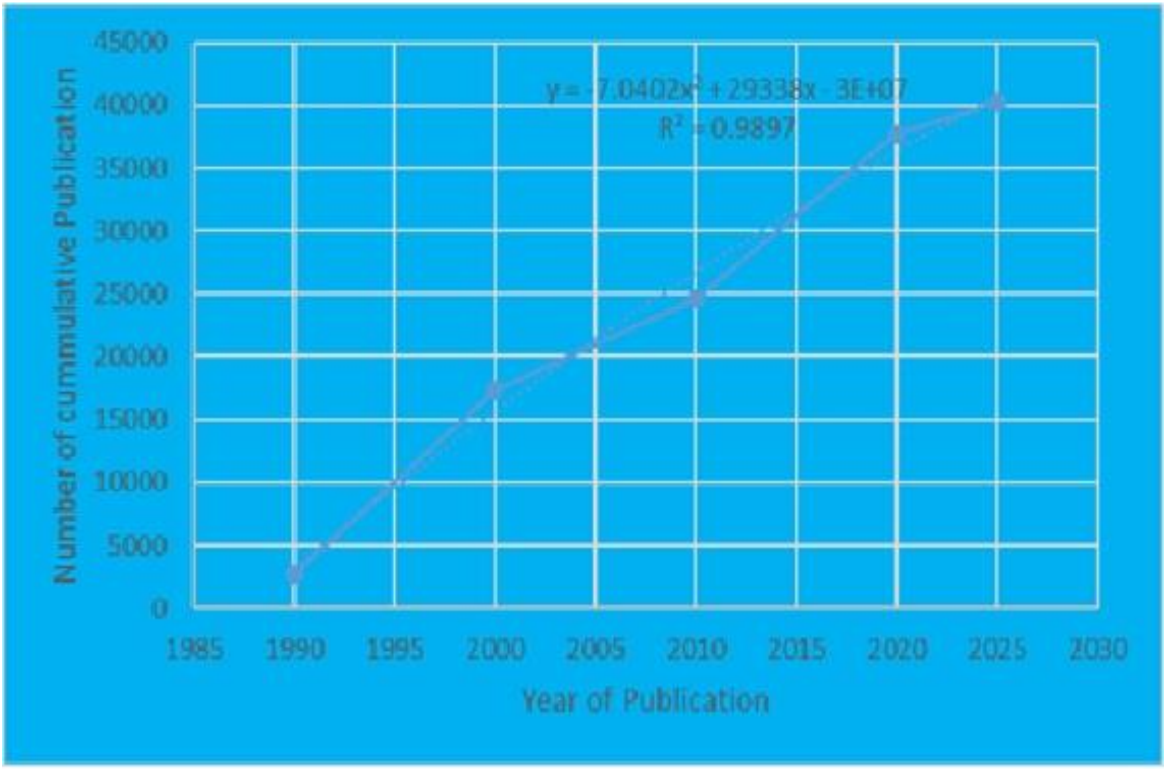


Figure 16 The growth of the cumulative articles on the keywords.

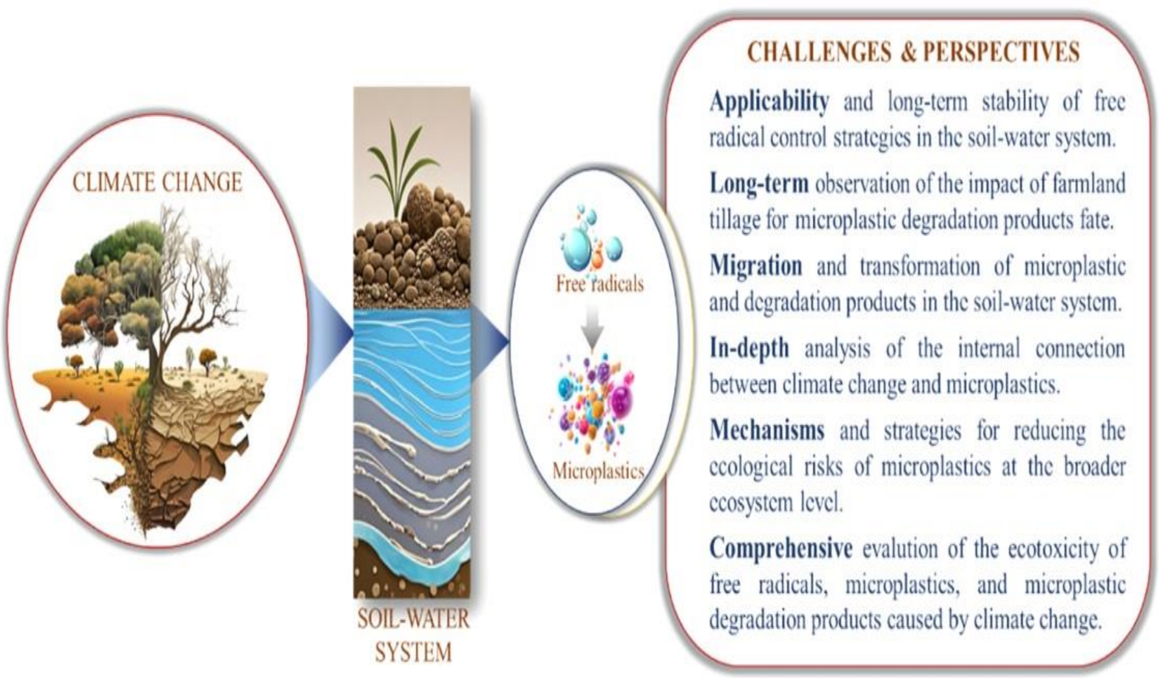


Figure 17 A proposed research framework on the impact of climate change on free radicals in the soil-water system regarding the degradation, migration, and toxicity of microplastics and nanoplastics (Source: Zhu et al., 2025).

Figure 11 shows the climate change influences the production of free radicals, subsequently impacting the environmental fate of microplastics. Figure 12 presents a schematic figure of possible uptake mechanisms and effects on plant growth of microplastics and nanoplastics by plants. Figure 13 shows the trophic transfer of MPs in soil and groundwater. Figure 14 shows the microplastics and nanoplastics contamination pathway from solid waste to agricultural soil. Figure 15 shows interactions between microplastics and nanoplastics sources and associated soil organisms as a risk pathway.

c) Research Findings on the distribution articles from the links and keywords

The summary of the articles on the keywords based on the links are PubMed link (2814), Taylor and Francis Online link (4422), ScienceDirect link (9246), Google Scholar link (38190), Web of Science link (2412), Elsevier link (6030), Scopus (6030), Magrian (2010), Wiley Online Library link (4824), SpringerLink (5628), American Chemical Society (ACS) Publications link (1206), MDPI link (1206), Frontiersin link (1608) and Royal Society of Chemistry (RSC) Publishing link (804), which indicates that google scholar has a lot of articles in it database than other links. Figure 16 presents the growth of the cumulative articles on the keywords. In addition, classification of articles availability based on the keywords chemistry of micro- and nano-plastics in soil-water and a bibliometric analysis and a literature review on chemistry of micro- and nano-plastics in soil-water revealed that chemistry of micro- and nonaplastic in soil-water, (26890), sediment of river (10965), and related environment (2345).

d) Challenges and perspectives

Climate change variations in free radicals within soil-water systems are universally observed, its effect on the distribution, transportation, migration, transformation, and eventual fate of microplastics and nanoplastics remains unclear. The synergistic effects and impact of climate change, soil-water environments, and free radicals are of considerable significance. These interactions are not only influence the ingestion and accumulation of microplastics and nanoplastics by organisms but may also enhance the biotoxicity of microplastics and nanoplastics.

It is expected that interdisciplinary techniques and approaches with long-term monitoring will lead to a profound understanding of the environmental behaviours of microplastics and nanoplastics with their degradation products under climate change. Further studies are required in the mechanisms underlying the degradation, migration, distribution, and ecotoxicity of microplastics and nanoplastics with their derivatives, driven by vigorously changed free radicals in response to climate change to enable the formulation of more effective environmental protection techniques to address the significant challenges posed by microplastics and nanoplastics pollution under complex climate conditions. Further information on challenges are documented in the literature such as Maddison et al.(2023); Chen et al. (2022); Ding et al. (2022b); Palansooriya et al. (2022); Zhang et al. (2024); Del Buono (2021) and Yuan et al.(2022). Figure 17 presents a proposed research framework on the impact of climate change on free radicals in the soil-water system regarding the degradation, migration, and toxicity of microplastics and nanoplastics.

CONCLUSIONS

It can be concluded that nanoplastics and microplastic pollution have become a significant global concern, adversely impacting ecosystem integrity and human health. Soil-water systems act as serious reservoirs for nanoplastics and microplastics and hotspots for the generation of free radicals. Fluctuations in free radicals within soil-water systems influence the degradation mechanisms, impact on reaction kinetics, and affect the transformation products of nanoplastics and microplastics. Future research and studies should prioritise long-term monitoring of free radicals and soil-water relationships to elucidate the specific mechanisms by which various climatic conditions can impact free radical generation through alterations in the physical, chemical, and biological environments of soil-water systems.

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