SCIENCE FORUM (JOURNAL OF PURE AND APPLIED SCIENCES) 25, (3) (2025), 102 - 119

Science Forum (Journal of Pure and Applied Sciences)

Journal Homepage: https://atbuscienceforum.com.ng/index.php/jpas

Mechanisms of Microplastics and Nanoplastics Removal from Air, Water and Soil: A Brief Review

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Abstract

Microplastics (MPs) and nanoplastics (NPs) are among the most critical emerging contaminants of the 21st century, posing complex challenges to researchers, policymakers, and the global scientific community due to their widespread distribution, persistence, and adverse impacts on human health and the environment. Despite growing awareness of their ecological and toxicological significance, the development and implementation of effective treatment and removal technologies for MPs and NPs in environmental media—particularly air, water, and soil—remain limited and fragmented across the literature. This study presents a comprehensive review and bibliometric analysis of existing treatment and removal techniques for MPs and NPs across various environmental matrices. Relevant data and publications were systematically sourced from reputable databases including PubMed, Taylor & Francis Online, ScienceDirect, and Google Scholar using carefully selected keywords such as *"removal techniques of micro- and nano-plastics from water, air, and soil."* Findings reveal that current treatment technologies encompass a diverse range of physical, chemical, and biological processes, including membrane filtration, advanced oxidation processes (AOPs), electrocoagulation, nanotechnology-based systems, bioremediation, mycoremediation, dissolved air flotation, grit chambers, anaerobic–anoxic–oxic (A2O) systems, activated sludge processes, sand and rapid sand filtration, granular activated carbon adsorption, and hybrid integrated approaches. The effectiveness of these technologies is largely dependent on several factors such as particle size distribution, polymer type, concentration of pollutants, process optimization, and site-specific environmental conditions. The study concludes that while numerous treatment strategies show promise, their scalability, cost-effectiveness, and sustainability remain key concerns. Future research should therefore emphasize the integration of advanced materials, green technologies, and circular economy principles to enhance the sustainable removal and recovery of micro- and nanoplastics from the environment.

Keywords
Micro and Nano-plastics; Environmental Pollution; Treatment Techniques; Emerging Contaminants; Bioremediation

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INTRODUCTION

Plastics are polymer organic materials synthesised through polycondensation or polyaddition of monomers (Styrene, Vinyl chloride, Propylene, and Ethylene), organic compounds as raw materials (Li et al., 2024). Plastics have been utilised in several industries due to their low cost, corrosion resistance, and high plasticity of plastics. Comprehensively, plastic solid waste rose from 353.0×10^6 tonnes in 2019 to 529.0×10^6 tonnes in 2023, as 22 % of plastics were directly discarded after utilise and exposed to the environment (OECD, 2023; Li et al., 2024).

Plastics entered the environment in large quantities and were deposited in both aquatic and terrestrial environments. It has been documented that a total of 710.0×10^6 tonnes (Lau et al., 2020; Li et al., 2024). Physically, biologically or photochemically processes degrade large-sized plastic fragments into small-sized particles (spheres, debris, sheets, foam, fibres, wires, and films (Li et al., 2024 Xu et al., 2020; 2023; Yang et al., 2021a, b, c and 2024; Sadek et al., 2025).

Micro and nano-plastics were introduced into the scientific community and widely recognised as fine particles with a particle size (Sun et al., 2020;2022; 2024 Li et al., 2024). The global estimated cumulative amount of micro and nano-plastics in agricultural soils is between 1.5 and 6.6×10^6 tons (Kedzierski et al., 2023; Li et al., 2024), which could be between 4.0 and 23.0 times that of the marine systems (He et al., 2018; 2022a and b; He, 2022; Mondal et al., 2025).

Furthermore, micro and nano-plastics are with a strong “carrier effect” of heavy metals and other pollutants in the soil, resulting in severe combined environmental pollution. This adsorption process is influenced by multiple factors (He et al., 2022a; He et al., 2022b; Hüffer et al., 2019; P´aez-Osuna et al., 2023; Wei et al., 2023; Zeleznikar et al., 2025; Wang et al., 2024).

Currently, poly-ethylene, polycarbonate, polystyrene, polyethylene terephthalate, polyvinyl chloride, and other plastics are produced in substantial amounts and are widely used in daily life (Yang et al., 2023).

A considerable quantity of plastics is discarded and persists in the environment after use, which creates micro- and nano-plastic pollutions in the environment. Figure 1 presents the key sources and fates of nanoplastic and microplastics in the soil and ecosystem. Figure 2 shows the dangers of microplastics and nanoplastic in the soil. Figure 3 shows estimated micro- and nano-plastic flow in typical wastewater treatment plants with primary, secondary, and tertiary treatment processes.

Micro- and nano-plastics pollution has been a widespread scientific concern in recent decades due to a large volume and quantity of discarded plastic flooding into the environment with a constant increase in plastics production and the presence of the same in the environment for a long time. which is the source of microplastic pollution. Many studies and documents have focused on marine, terrestrial and soil micro- and nano-plastic pollutions, but little or very few provide information on removal techniques in water, air, and soil, and it is significant to pay attention to micro- and nano-plastic removal from water, air, and soil. The main focus of this study is to provide a basic review of the removal techniques of micro- and nano-plastics in water, air, and soil (Saljinkovk et al., 2025; Pradhan et al., 2023; Pan et al., 2024b; Mota et al., 2025).

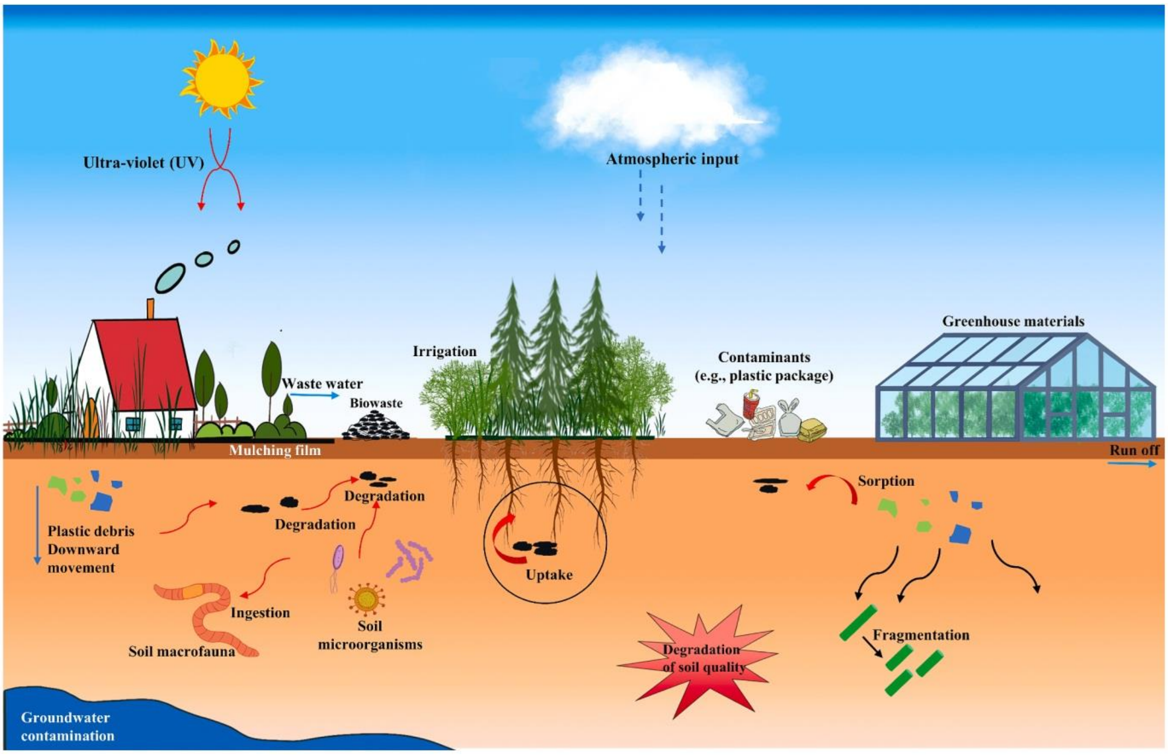


Figure 1: the key sources and fates of nanoplastic and microplastics in the soil and ecosystem. (Source: Pan et al., 2024a)

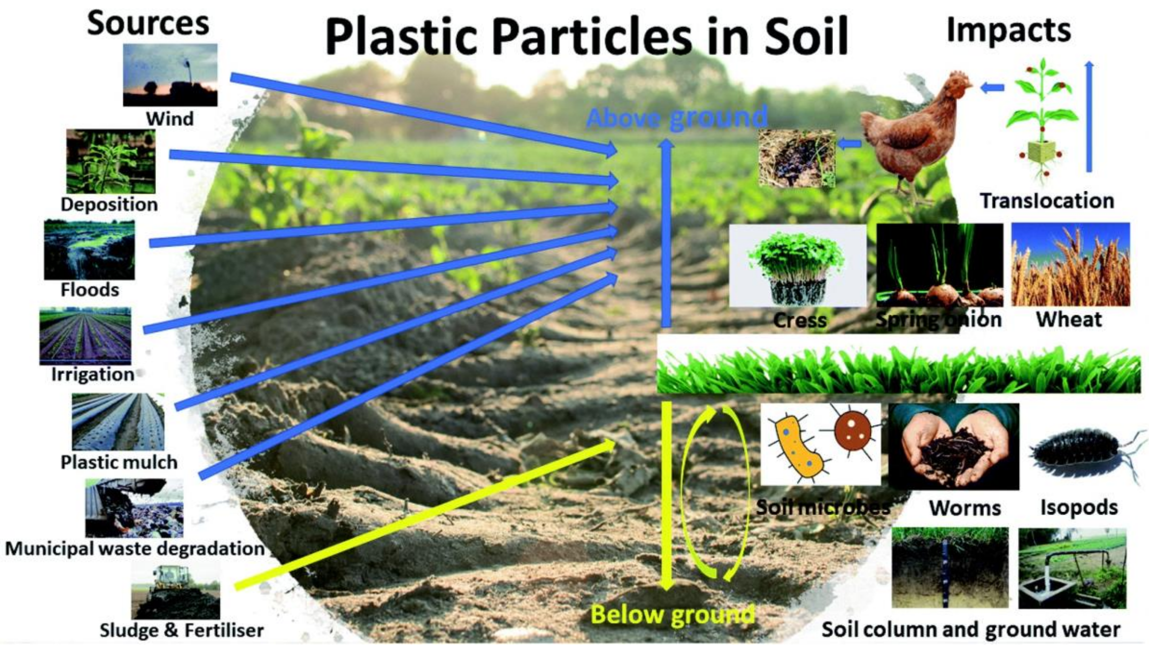


Figure 2: The dangers of microplastics and nanoplastic in the soil (Source: Images 2025)

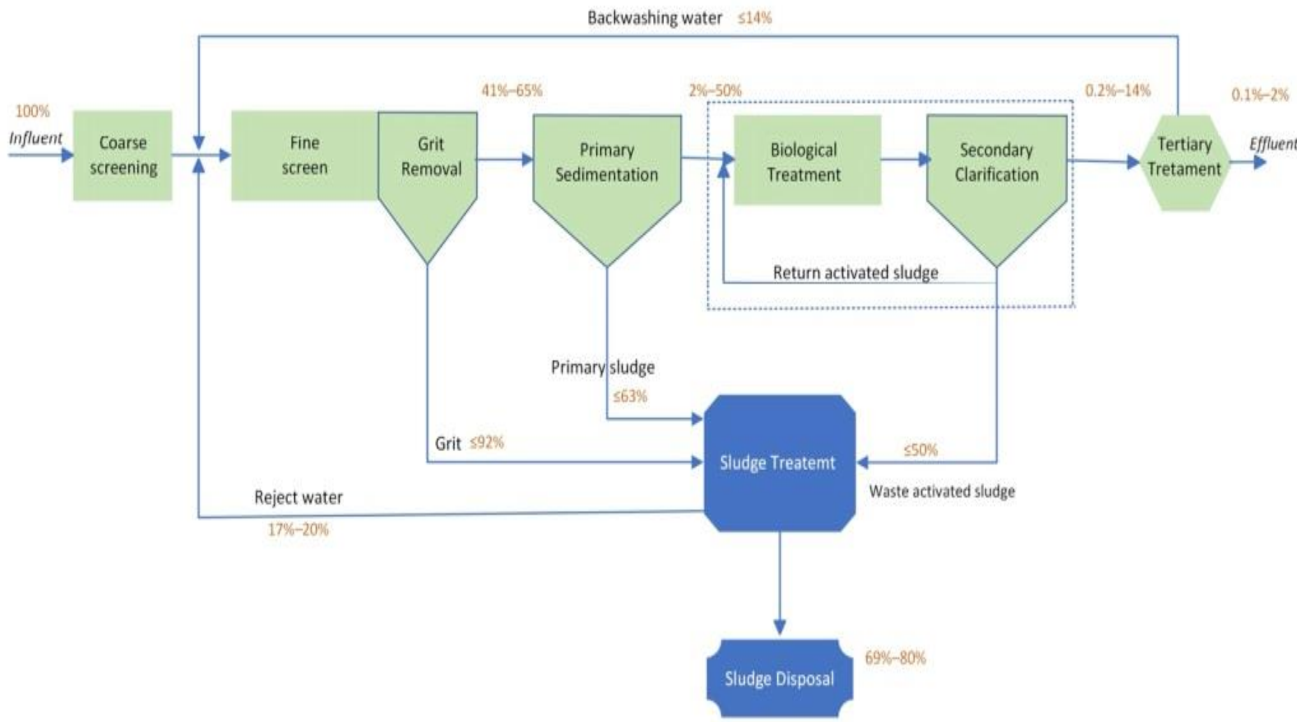


Figure 3 estimated micro- and nano-plastic flow in typical wastewater treatment plants with primary, secondary, and tertiary treatment processes (Source: Jani et al., 2024)

MATERIALS AND METHODS

In this dynamic and vital study on mechanisms of microplastics and nanoplastics removal from air, water and soil, 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 American Chemical Society (ACS) Publications link (http://pubs.acs.org), Elsevier link (https://www.elsevier.com/), Frontiersin link (https://www.frontiersin.org), Google Scholar link (https:// scholar.google.com/), Magiran link (https://www.magiran.com/), MDPI link (https://www.mdpi.com/), PubMed link (https://www.pubmed.ncbi. nlm.nih.gov), Royal Society of Chemistry (RSC) Publishing link (http://pubs.rsc.org), ScienceDirect link (http://www.sciencedirect.com/), Scopus link (https:// www.scopus.com/), SpringerLink (http://link.springer.com/), Taylor and Francis Online link (http://www.tandfonline.com/), Web of Science link (https://webofknowledge.com/), and Wiley Online Library link (http://onlinelibrary.wiley.com/), using the keywords: removal techniques of micro- and nano-plastics from water, air, and soil and a bibliometric analysis and a literature review on removal techniques of micro- and nano-plastics from water, air, and soil. The outcome of the literature search was analysed using Microsoft Excel (analysis of variance).

Literature Review on Micro and Nano-Plastics Treatment Techniques

Literature review on micro- and nano-plastic treatment techniques is presented in the following categories as follows:

a. **Removal Techniques from Water (Surface and Groundwater)**

Ravindiran et al. (2023) summarised groundwater utilisation in various sectors, potential sources of groundwater contamination, impacts on human health and the environment, and preventive measures and mitigation methods to overcome groundwater pollution. The study revealed that remediation techniques for the removal of micro- and nano-plastics are oxygen sparging, air stripping, stream stripping, bioremediation, chemical oxidation and thermal treatment, while prevention techniques include health education, monitoring hazardous materials, and conducting periodic environmental audits. Jani et al. (2024) provided a detailed examination of contemporary methodologies for sampling, detecting, and eliminating micro- and nano-plastics.

It was concluded that physical and chemical extraction techniques are applied to extract micro- and nano-plastics in wastewater treatment plants. In the chemical extraction technique, several digestion protocols such as hydrogen peroxide, Fenton's reagents, acid-based, and alkaline-based techniques are applied. Figure 4 presents the techniques used for micro- and nano-plastic detection in wastewater treatment plants. Peng et al. (2024) studied biohybrid microrobots, integrating the magnetic properties of Fe_3O_4 nanoparticles for the dynamic removal of micro-nano-plastics from various aquatic environments through high-precision magnetic actuation and reliable electrostatic interactions. It was concluded that magnetic algae robots display considerable capture and removal efficiencies for micro-nano-plastics in water with extensive application scenarios. Figure 7 shows biohybrid magnetic algae robot for effective removal of micro-nano-plastics from water. Rout et al. (2022) evaluated the treatment processes presently employed for micro- and nano-plastics removal in wastewater treatment plants to upgrade the existing designs further. It was concluded that the advanced treatment processes, such as membrane technologies, advanced oxidation process, electro-coagulation, nano technology can remove micro- and nano-plastics from wastewaters. It was highlighted that possible toxic microbial biotransformation of micro- and nano-plastics during biological treatment steps in wastewater treatment plants needs to be taken care of through further in-depth research.

As a basic knowledge of removal mechanisms in wastewater treatment plants could reduce the environmental pervasiveness of micro- and nano-plastics. Figure 8 shows the overview of micro- and nano-plastics removal mechanisms in wastewater treatment plants. Figure 9 presents the micro- and nano-plastics removal mechanism in membrane-based technologies. Di Luca et al. (2025) evaluated photo-Fenton oxidation of polystyrene nanoplastics. The study examined selected reaction parameters particle size of micro- and nano-plastics, agitation speed, and operating temperature) affecting the oxidation rate of micro- and nano-plastics. The study revealed that the overall reaction rate was divided into two stages, following a free-radical mechanism. It was concluded that the proposed mechanisms and models provide valuable insights for describing and predicting the advanced oxidation of micro- and nano-plastics under different operating conditions and treatment methods.

b. Removal Techniques from Soil

Li et al. (2024) provided scientific guidance for the remediation and management of micro- and nano-plastics and cadmium joint exposure soil environments. Figure 5 presents the adsorption mechanism of heavy metal pollutants on micro- and nano-plastics. Figure 6 shows the ecological impacts and effects of interaction and combined pollution between micro- and nano-plastics and heavy metals in the soil. Dignac et al. (2024) stated that to protect soils from micro and nano-plastics pollution, a strong global treaty is needed, with provisions on plastic production reduction, product design and regulation of plastic chemicals. Plastics' essentiality, sustainability and safety criteria are required in the agriculture sector, where plastics are utilised unsustainably and not all are essential, and in all sectors along the food production value chain (food processing, packaging).

Huang et al. (2025) quantified the contribution of micro and nano- plastics to organic carbon stocks in seagrass bed sediments and underscored the urgent need for seagrass conservation to mitigate climate change and prevent the remobilisation of historically buried micro- and nano- plastics. Ramanayaka et al. (2024) inspected the propensity of frequently utilised plastic additives in mulch films Di(2-ethylhexyl) phthalate, bisphenol A and benzophenones, to migrate into soils and pose potential risks to soil biota.

It was reported that exposure of micro- and nano-plastics to ultraviolet radiation and microbial activities accelerates the weathering of mulch films. Xu et al. (2024) critically summarised the effects of photo-oxidation on the physical, chemical, and biological behaviours of micro- and nano-plastics in aquatic and terrestrial environments. The study provided the photochemical processes of micro- and nano-plastics with coexisting constituents, highlighting critical factors affecting the photo-oxidation of micro- and nano-plastics, and the contribution of micro- and nano-plastics to the photo-transformation of other contaminants. Figure 10 presents the effect of photo-oxidation of micro- and nano-plastics on the homo-aggregation, hetero-aggregation, and adsorption behaviours toward pollutants.

Figure 11 shows the photochemical processes of micro- and nano-plastics with coexisting natural constituents and pollutants. Figure 12 shows the biological effects of micro- and nano-plastics after photo-oxidation. Yusuf et al. (2022) presented a critical review covering sulphate radical activation methods and mechanisms, the influence of operating conditions on sulphate radical generation and oxidative efficiency, and applications of catalytic sulphate radical-based advanced oxidation process for the removal of micro- and nano-plastics. It was concluded that the catalytic sulphate radical-based advanced oxidation process also holds future promise for drinking water treatment and total mineralisation.

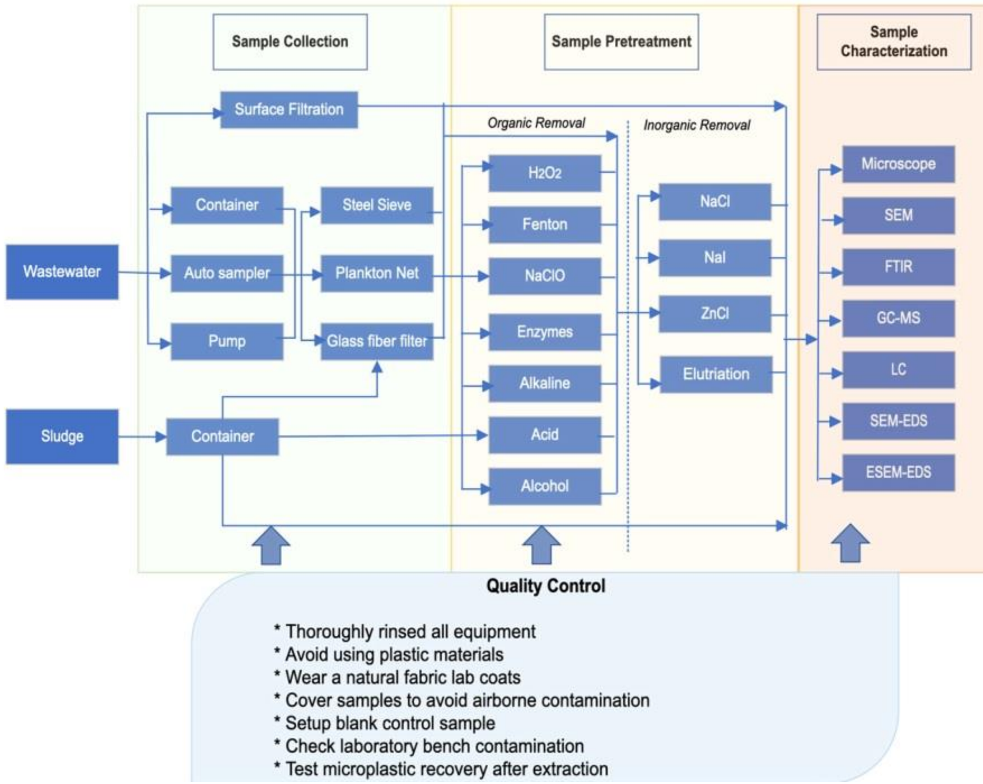


Figure 4: The techniques used for micro- and nano-plastic detection in wastewater treatment plants (source: Jani et al., 2024)

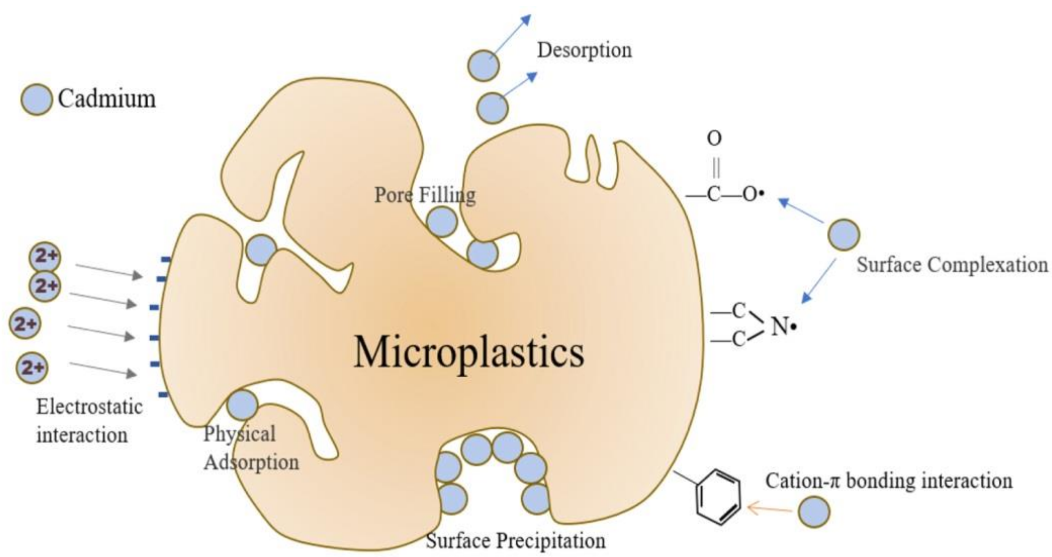


Figure 5: The adsorption mechanism of heavy metal pollutants on micro- and nano-plastics (Source: Li et al. 2024).

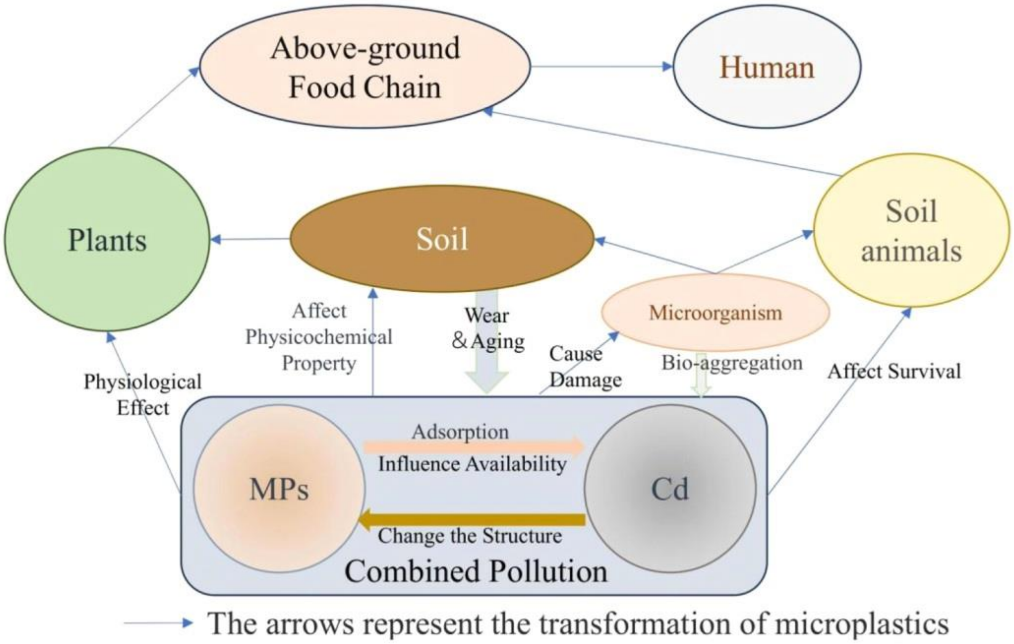
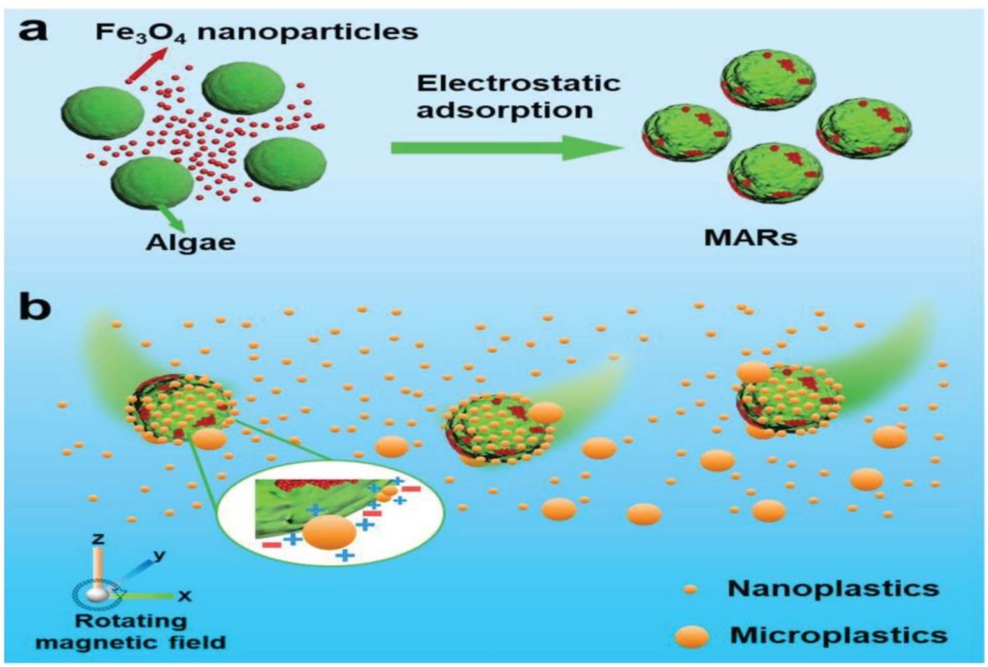


Figure 6 the ecological impacts and effects of interaction and combined pollution between micro- and nano-plastics and heavy metals in soil (Source: Li et al. 2024).



a) Bare algae cells integrated Fe3O4 nanoparticles on the surface via electrostatic absorption.

b) Utilizing magnetic actuation and electrostatic interactions, MARs facilitate the removal of micro/nanoplastics from water by drawing them to their surface.

Figure 7: The biohybrid magnetic algae robot for effective removal of micro-nano-plastics from water (Source: Peng et al. 2024).

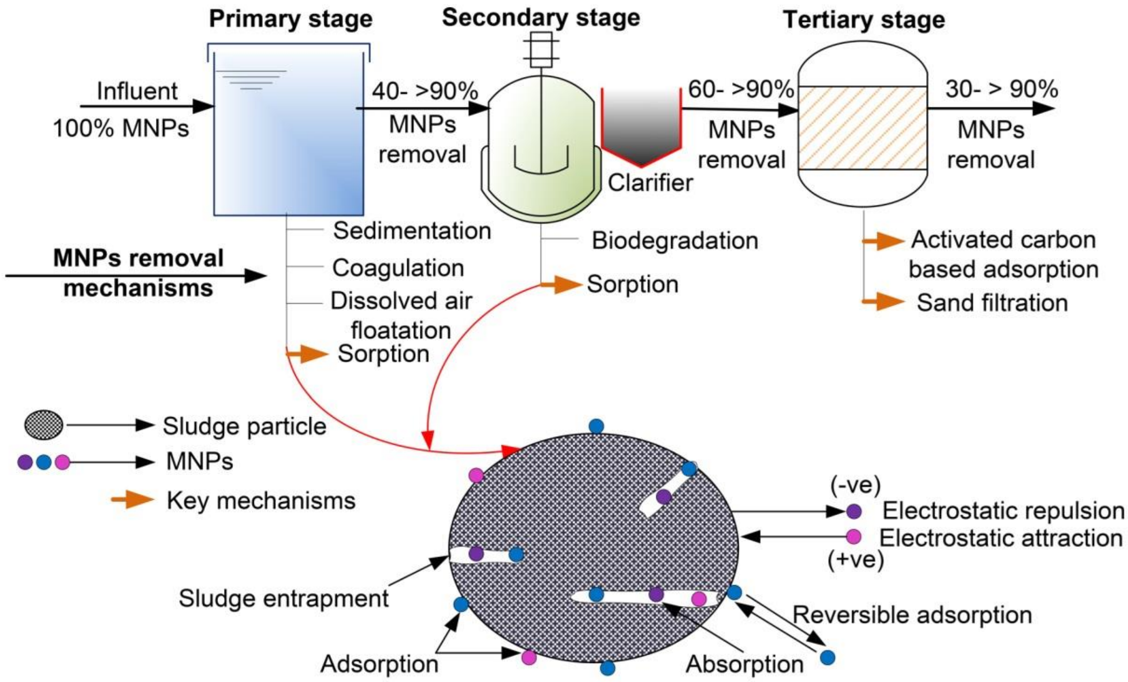


Figure 8 the overview of micro- and nano-plastics removal mechanisms in wastewater treatment plants (Source: Rout et al. 2022).

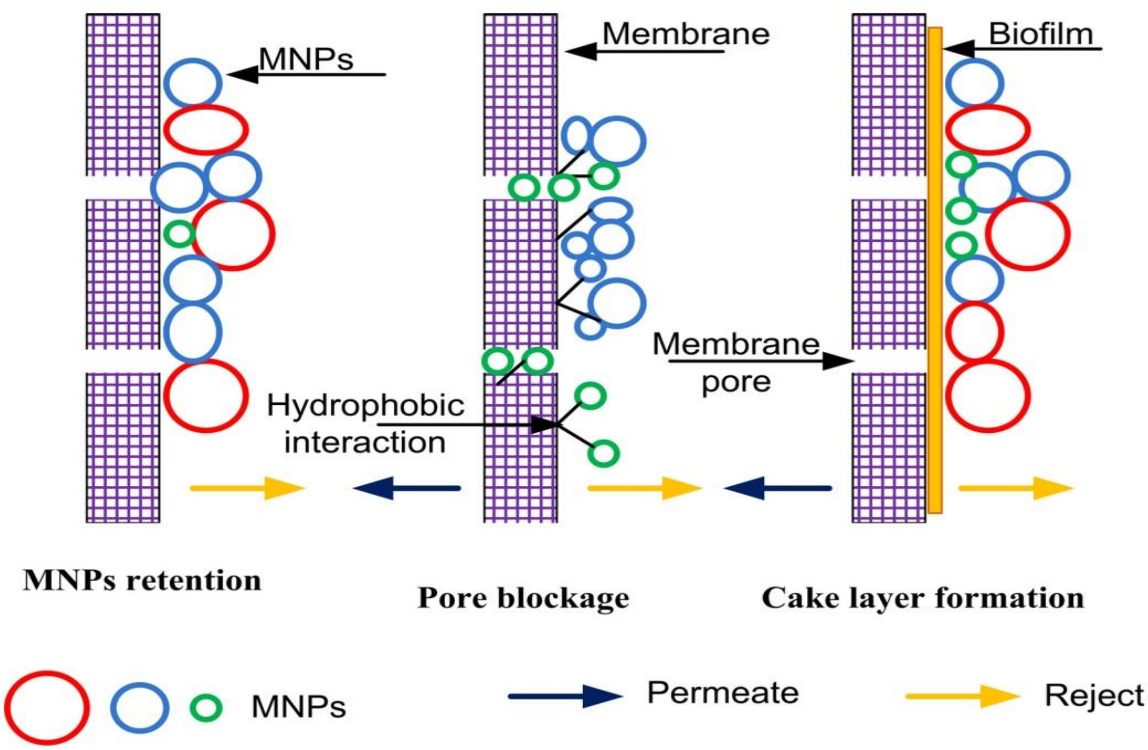


Figure 9 the micro- and nano-plastics removal mechanism in membrane-based technologies. (Source: Rout et al. 2022).

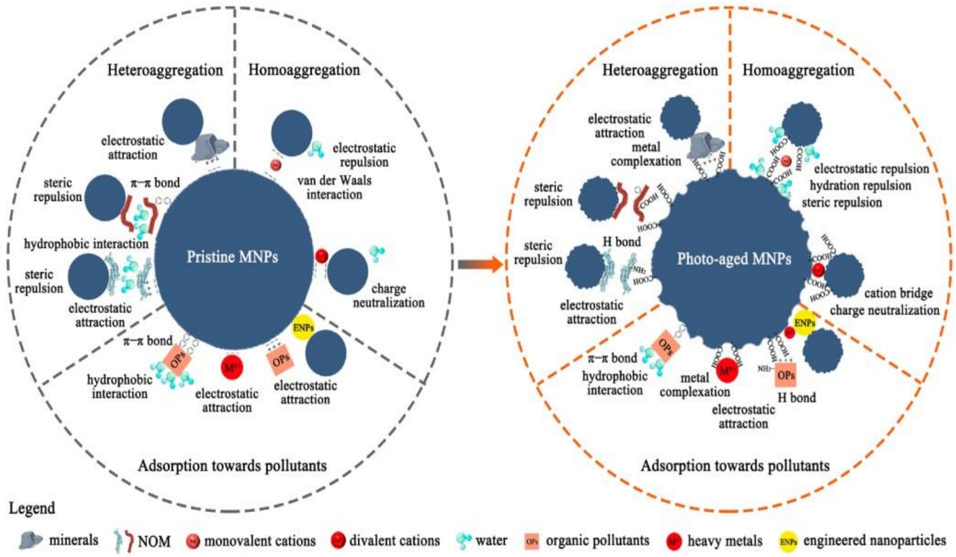


Figure 10 The effect of photo-oxidation of micro- and nano-plastics on the homo-aggregation, hetero-aggregation, and adsorption behaviours toward pollutants. (Source: Xu et al. 2024).

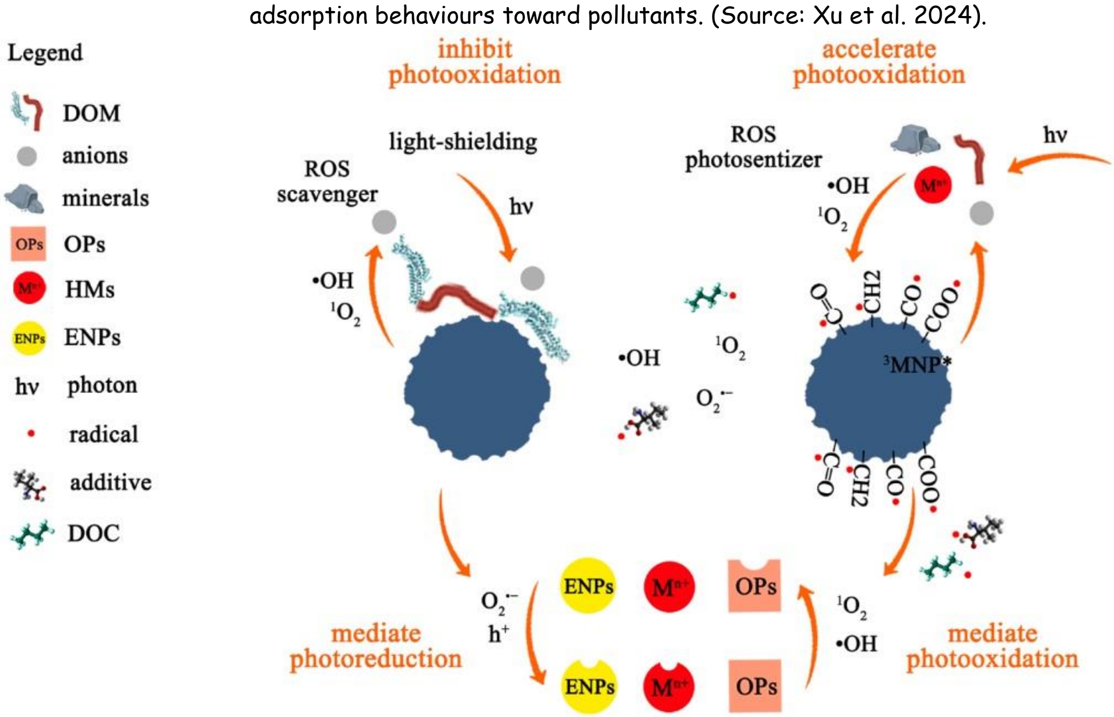


Figure 11 The photochemical processes of micro- and nano-plastics with coexisting natural constituents and pollutants (Source:Xu et al. 2024).

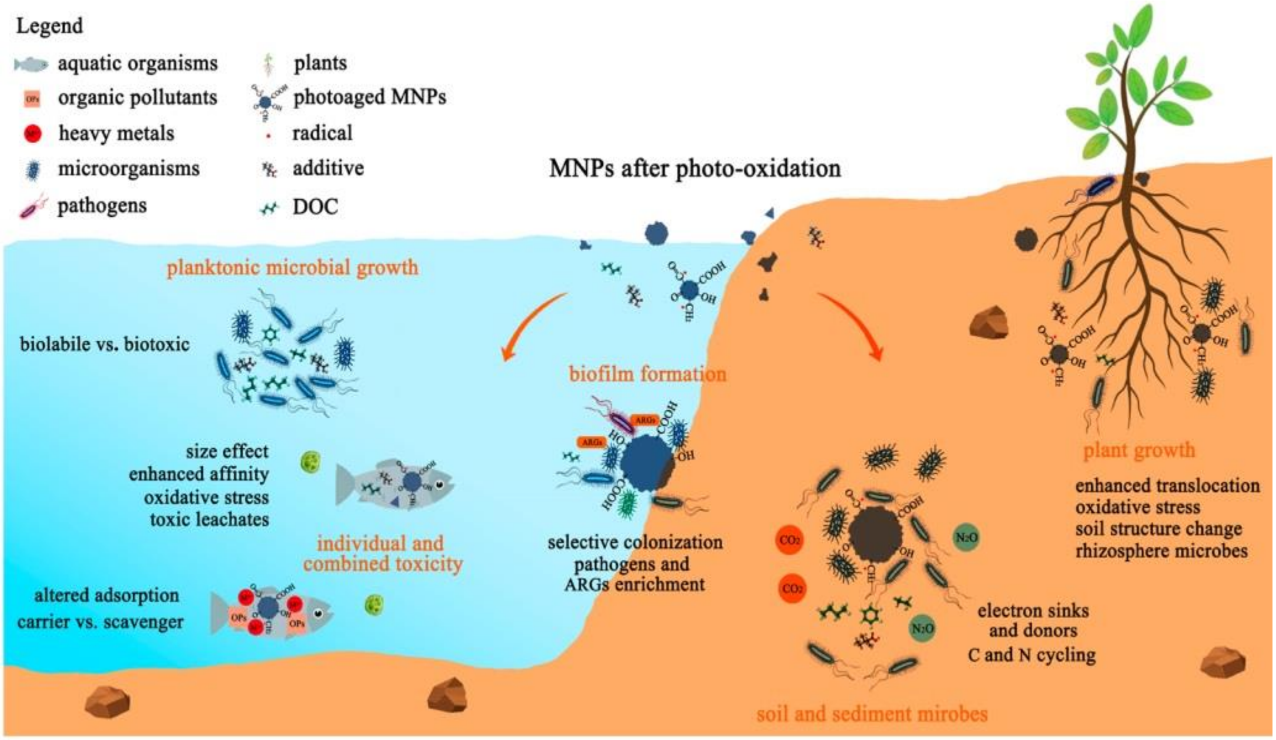


Figure 12: the biological effects of micro- and nano-plastics after photo-oxidation.
(Source: Xu et al. 2024).

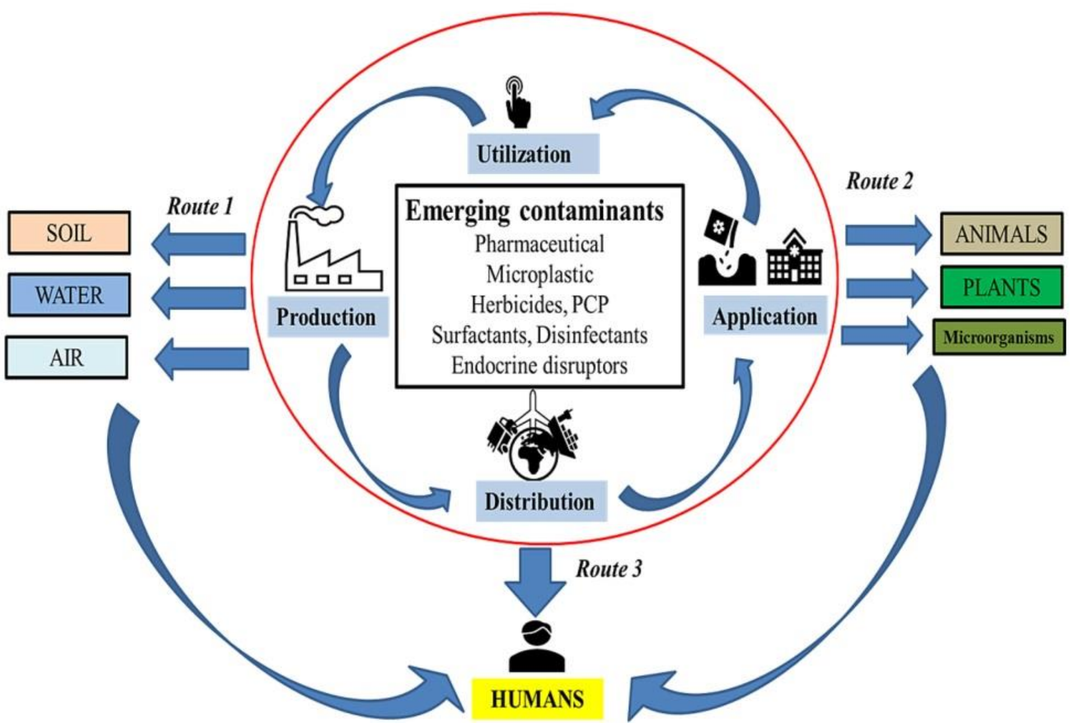


Figure 13 presents the distribution of micro- and nano-plastics in various environmental matrices.
(Source: Yusuf et al. 2022).

Figure 13 presents the distribution of micro- and nano-plastics in various environmental matrices. Vaksmaa et al. (2023) focused on the mycoremediation of micro- and nano-plastics in aquatic environments. It was concluded that fungi have the ability to break down pesticides, pharmaceuticals and personal care products, plastics, both conventional types and bioplastics, and fungal a role in the mitigation of heavy metal pollution. Pandey et al. (2022) examined the present creative solutions in water treatment from an Industry-4.0 viewpoint, focusing on big data, the Internet of Things, artificial intelligence, and several other technologies.

c. Removal Techniques from Air

Mensah et al. (2024) provided evidence that suspended nanobubbles can remove nanoplastics when repulsive coulombic forces between nanobubbles and nanoplastics are subdued. The study concluded that the study paves the way forward for engineering systems where coagulation and flotation can deliberately contribute to the removal of nanoplastics with the utility of nanobubbles. More on the removal of fine particles such as micro- and nano-plastics from the air can be established in the literature, such as Ośko et al. (2025); Sheng-chao et al. (2025); Yuan et al. (2025); Zheng et al. (2024); Geiss et al. (2024); Roy (2019); Boskovic and Agranovski (2010); D'Addio et al. (2014); Jaworek et al. (2018); Parisi et al. (2025); Mensah et al., 2025; Kumar et al., 2025; Gulzar et al., 2025; Gong et al., 2025 and Moreira et al. (2025).

Research Findings

The summary of the articles on the keywords based on the links are PubMed link (2898), Taylor and Francis Online link (4554), ScienceDirect link (9522), Google Scholar link (39330), Web of Science link (2484), Elsevier link (6210), Wiley Online Library link (4968), SpringerLink (5796), American Chemical Society (ACS) Publications link (1242), MDPI link (414), Frontiersin link (1656) and Royal Society of Chemistry (RSC) Publishing link

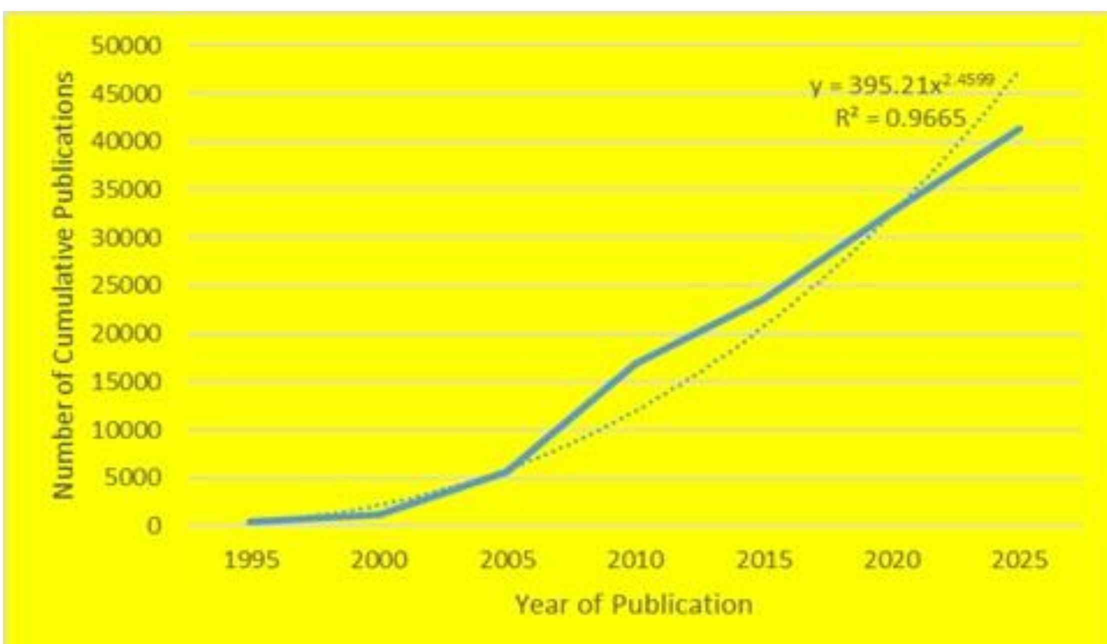


Figure 14: The growth of the cumulative articles on the keywords

(828), which indicates that google scholar has a lot of articles in it database than other links. Figure 14 presents the growth of the cumulative articles on the keywords. In addition, classification of articles availability based on the keywords mechanisms of removal techniques of micro- and nano-plastics from water, air, and soil and a bibliometric analysis and a literature review on mechanisms of removal techniques of micro- and nano-plastics from water, air, and soil revealed that mechanisms of removal of micro- and nonaplastic from water, aquatic, marine, sea and related environment (28456), mechanisms of removal of micro- and nonaplastic from soil, farmland, agricultural soils and similar environment (12691), and removal of micro- and nonaplastic from the air (253).

More on the removal of plastic particles such as can be established in the literature, such as Hamidian et al. (2025); Gong et al. (2025); Esmaeili et al. (2023); Dignac et al. (2025); Devi et al. (2022); de la Asunción-Nadal et al. (2024); Choudhary et al. (2024); Biermann et al. (2025); Berenstein et al. (2024); Bere et al. (2025), and Amir et al. (2025).

CONCLUSION

The study concluded that treatment processes utilised for the removal of micro- and nanoplastics from the environment (water, air and soil) are membrane technologies, advanced oxidation process, electro-coagulation, nano technology, bioremediation, dissolved air flotation, mycoremediation, grit chamber, anaerobic, anoxic and oxic processes, activated sludge process, sand filtration, rapid sand filtration, granular activated carbon, adsorption. The efficacy of the mechanisms of these techniques is a function of many factors, such as variations in the quantity of pollutants, the selected treatment technique to be utilised, and the sustainability of the techniques and the key factors.

ACKNOWLEDGEMENT

The authors wish to acknowledge Miss OKOLI Chineye Mary-Cynthia and .Miss. Aladekomo, J.O. of the Department of Civil Engineering, Obafemi Awolowo University, Ile-Ife, for their input and vetting of the arrangement of the manuscript.

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