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Microplastics in soils during the COVID-19 pandemic: Sources, migration and transformations, and remediation technologies



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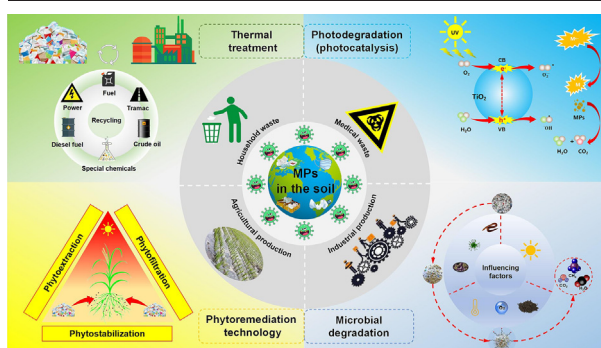
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HIGHLIGHTS

- Soil is a sink for all kinds of MPs during the COVID-19 pandemic.
- MPs in soil will affect soil structure, organisms, and human health.
- Some technologies are not suitable for the remediation of MPs in soil.
- MPs can be controlled from both sources and processes after the COVID-19.
- New technologies for the remediation of MPs in soil are still needed in the post-pandemic era.

GRAPHICAL ABSTRACT



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ABSTRACT

The COVID-19 pandemic has led to a notable upsurge of 5–10 % in global plastic production, which could have potential implications on the soil quality through increased microplastics (MPs) content. The elevated levels of MPs in the soil poses a significant threat to both the environment and human health, hence necessitating the remediation of MPs in the environment. Despite the significant attention given to MPs remediation in aqueous environments, less consideration has been given to MPs remediation in the soil. Consequently, this review highlights the major sources of MPs in the soil, their migration and transformation behaviors during the COVID-19 pandemic, and emphasizes the importance of utilizing remediation technologies such as phytoremediation, thermal treatment, microbial degradation, and photodegradation for MPs in the soil. Furthermore, this review provides a prospective outlook on potential future remediation methods for MPs in the soil. Although the COVID-19 pandemic is nearing its end, the long-term impact of MPs on the soil remains, making this review a valuable reference for the remediation of MPs in the post-pandemic soil.

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Nomenclature

PPE	Personal protective equipment
MSW	Municipal solid waste
MPs	Microplastics
HDPE	High-density polyethylene
LDPE	Low-density polyethylene
PS	Polystyrene
PAE	Phthalates
Brevis	<i>Brevibacillus brevis</i>
OC	Organic carbon
UV	Ultraviolet
NPs	Nanoplastics
PET	Polyethylene terephthalate
PVC	Polyvinyl chloride
PP	Polypropylene
PC	Polycarbonate
VOCs	Volatile organic compounds

1. Introduction

Plastics are polymers with great social benefits, and the vigorous development of modern plastics can be traced back to the 1950s with the synthesis of at least 15 new polymers. Plastics are widely used in human life because of their inherent light weight, durability, and versatility. However, their chemical resistance makes them resistant to degradation by microorganisms, leading to their persistence in the environment for extended periods of time (Chae and An, 2018; Engels et al., 2013; Wright and Kelly, 2017). Improper handling of plastics can result in environmental problems and harm to organisms (Chae and An, 2018; Provencher et al.,

2020; Verma et al., 2016), which has prompted extensive research into the impact of plastic waste on the environment in recent years. Although marine and freshwater ecosystems have been extensively studied, there has been relatively little attention paid to plastic pollution in soil ecosystems. Plastics in soil can be traced to various sources, including large plastic waste from roadsides, beaches, and streets (Ji et al., 2022), plastic mulch used in agriculture (Hayes, 2021), and microfibers from the wear and tear of textiles and tires (Song et al., 2017).

The COVID-19 pandemic necessitated the implementation of closure and control measures in numerous countries, aimed at curtailing the spread of the virus (El-Baz et al., 2020). This had the consequence of shutting down various factories, such as those in the electronics and food processing industries, which are known to have environmentally damaging effects (Park et al., 2020). These measures were initially viewed as environmentally friendly. However, the extensive use of personal protective equipment (PPE), coupled with the reliance on plastic packaging supplies due to residential containment at home or other isolated locations, has resulted in a considerable surge in plastic waste. Research estimates indicate that, on a daily basis, the global output of plastic waste stands at 1.6 million tons since the outbreak, with an additional 3.4 billion disposable masks/facepieces being discarded each day worldwide (Benson et al., 2021). Following the pandemic, a resumption of work and production will undoubtedly lead to an unmitigated rise in plastic waste generation, which poses a severe threat to the environment, perpetually hindering economic development.

Improper disposal of PPE during the epidemic has led to an increase in plastic waste accumulation in soil. Municipal plastic waste production worldwide surpassed 200 million tons in 2020, with approximately 43 % of it ending up in landfills, open dumps, or natural environments. The proportion of PPE in plastic waste in landfills has increased from 0.4 % in 2017 to 3.5 % in 2020 (Patrício Silva et al., 2021). Accordingly, it is estimated that the COVID-19 pandemic will increase global plastic production by 5 to 10 % from its onset to its conclusion. These additional plastics will ultimately end up distributed throughout land and marine systems. Research

has revealed that up to 80 % of plastic waste in oceans originates from land, with soil-based plastic waste ranging from 4 to 23 times higher than that found in the oceans (Sharma et al., 2020; Wang et al., 2022; Yang et al., 2021). Physical, chemical, and biological activities fragment disposed PPE into microplastics (MPs) and nanoplastics (NPs) ranging from 0.1 to 5 mm and 0.001–0.1 μm , respectively (Allouzi et al., 2021; Silva et al., 2021; Zhou et al., 2022). MPs and NPs can potentially interact with toxic elements in the environment, leading to soil toxicity, health deterioration when consumed by animals and humans (Ebere et al., 2019), and other dysfunctions such as cardiovascular system malfunctioning, oxidative stress, cellular damage, and inflammation (Qiao et al., 2019). Additionally, MPs and NPs adsorb organic pollutants and can disrupt the body's endocrine system, affecting reproductive health (Phu et al., 2022). Recent studies have revealed that MPs in meltblown mask filters can inhibit the reproduction, growth, and development of jumping worms, reduce esterase activity in earthworm body cavities, and inhibit spermatogenesis in the reproductive tissues of male earthworms (Kwak and An, 2021). MPs and NPs can also interact with soil organic debris, thereby contaminating groundwater and affecting soil's physicochemical properties (Allouzi et al., 2021; Liu et al., 2021).

The plastic waste generated during the pandemic is subject to weathering and mechanical degradation, resulting in plastic debris that can be further decomposed into MPs. The migration and transformation of MPs in soil can have a detrimental effect on the physicochemical properties of soil, groundwater, soil flora and fauna, and microbial communities, thereby posing a potential threat to human health. Urgent action is required to address the issue of MPs in soil. Fig. 1a is based on a Web of Science search that yielded 255 references to the keyword “microplastic degradation technologies” in the last 3 years, and then analyzed the entries using the visualization software VOSviewer. The results showed that most studies have focused on remediation efforts in aqueous or marine environments (Bansal et al., 2021; Elgarahy Ahmed et al., 2021; Rodríguez-Narvaez et al., 2021). However, there has been a lack of attention given to the remediation of MPs and NPs in the soil environment, despite the rapid increase in MPs caused by the COVID-19 pandemic. Mature technologies, such as membrane technology, which have been used to remediate MPs in the aqueous environment, have rarely been applied to remediate MPs in soil (Malankowska et al., 2021). Other treatment technologies, such as burning of plastics, produce harmful gases (CO_2 and dioxins), while landfilled plastics are difficult to degrade naturally in the soil (Verma et al., 2016). Consequently, further research is needed to identify measures or technologies that can be applied to the remediation of MPs in soil.

Therefore, the primary objective of this article is to present a comprehensive review of the primary sources of MPs in soil during pandemics, along with a discussion on the applicable remediation or treatment technologies for the removal of MPs from soil. The contamination of soil with MPs during the pandemic has prompted the need for remediation strategies, which are crucial for ensuring human health safety and the long-term sustainability of soil ecosystems. Furthermore, the study anticipates the emergence of new technologies for the degradation of MPs, which could provide valuable insights into the remediation of MPs in soils in a post-pandemic era.

2. Main sources of MPs in soils during the COVID-19 pandemic

Common plastics are polymers such as polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), and polycarbonate (PC). The recycling rate of these plastics varies depending on the type, with PS and LDPE exhibiting low recycling rates, PET and HDPE exhibiting high recycling rates, while PVC and PP are rarely recycled (Alabi Okunola et al., 2019; Di et al., 2021; Rahimi and García, 2017). During the COVID-19 pandemic, MPs have been produced from a variety of sources, including medical waste, domestic waste, industrial, and agricultural production, as shown in Fig. 1b. Plastic wastes from these sources are collected, transported, and deposited in landfills and open dumps, where they undergo various physicochemical and biological transformations, including mechanical

degradation, weathering, photodegradation, and biodegradation. These transformations result in the formation of highly contaminated wastewater in the form of leachate, which contains large amounts of MPs, as well as metals and other organic materials. If left untreated, these leachates may flow into the soil, surface water, or groundwater, causing further compound contamination (Silva et al., 2021; Thaiyal et al., 2022). Therefore, it is crucial to identify the sources of plastic wastes and implement measures to reduce their accumulation in soils to minimize their impact on human health and environmental sustainability.

2.1. Medical waste

In the context of an outbreak, there is often a surge in the number of individuals infected with a particular disease, leading to an increased demand for medical resources such as personnel, supplies, and facilities. Unfortunately, this increase in medical activity inevitably leads to a significant amount of medical waste, which the World Health Organization (WHO) defines as waste generated during the diagnosis, treatment, or immunization of humans or animals (Yu et al., 2020). Medical waste is primarily composed of plastics, paper, and textiles, which are the main raw materials used in medical supplies (Chen et al., 2013). These wastes are often characterized by their radioactivity, complexity, infectiousness, and toxicity, which pose a significant threat to both the ecological environment and human health if not treated properly (Manga et al., 2011; Windfeld and Brooks, 2015). In particular, plastic waste is a significant component of medical waste, mainly from disposable PPE and medical equipment.

Disposable masks (medical and non-medical), protective clothing, masks, nitrile gloves, goggles, respirators, medical bottles, infusion sets, medical test kits, and discarded syringes (plastic parts) are among the PPE and medical equipment that generate plastic waste (Su et al., 2021; Zhao et al., 2021). The increased demand for medical products and packaging during the epidemic has led to a significant increase in global plastic waste generation. The WHO estimates that approximately 89 million masks, 76 million gloves, 30 million gowns, 1.6 million goggles, and 2.9 million hand sanitizers are needed globally each month to deal with the current spread of the new coronavirus (WHO, 2020). Various studies have investigated the relationship between daily mask use and medical waste generation in different countries (Fig. 1c). For instance, Sangkham (2020) investigated the number of masks and medical waste used in Asian countries in the COVID-19 pandemic database. Mahmoudnia et al. (2022) used equations to estimate the daily use of masks and gloves in other countries during the pandemic period. These studies showed that the daily mask use and medical waste generation in each country were mainly related to the population of the country, the acceptance rate of mask or glove use, the average number of masks worn per person per day, and the number of confirmed cases. Additionally, the country's level of economic development, waste management practices, and environmental awareness also play a crucial role.

2.2. Household waste

The COVID-19 pandemic has resulted in widespread closures of homes, restaurants, and supermarkets in various regions worldwide. Despite this, the take-out industry has experienced a relatively lesser impact (Kochańska et al., 2021). The subsequent shortage of household goods and food has prompted a significant surge in online purchasing power among the populace, leading to a substantial increase in household waste. This waste comprises various items such as female cosmetics, beverage bottles, disposable tableware, purchase bags, aquatic fish, shrimp and seafood, pork, sheep and beef, salt, rice, fruits, and vegetables. Packaging and film materials constitute a significant proportion of this waste. The plastic packaging materials include HDPE, LDPE, PET, garbage bags, and other plastics, whereas plastic films are categorized as pure or composite plastics. These films primarily comprise single-use plastics derived from petroleum-based polymers, which have been acknowledged as effective and economical packaging materials (Oliveira de et al., 2021; Shi et al., 2023).

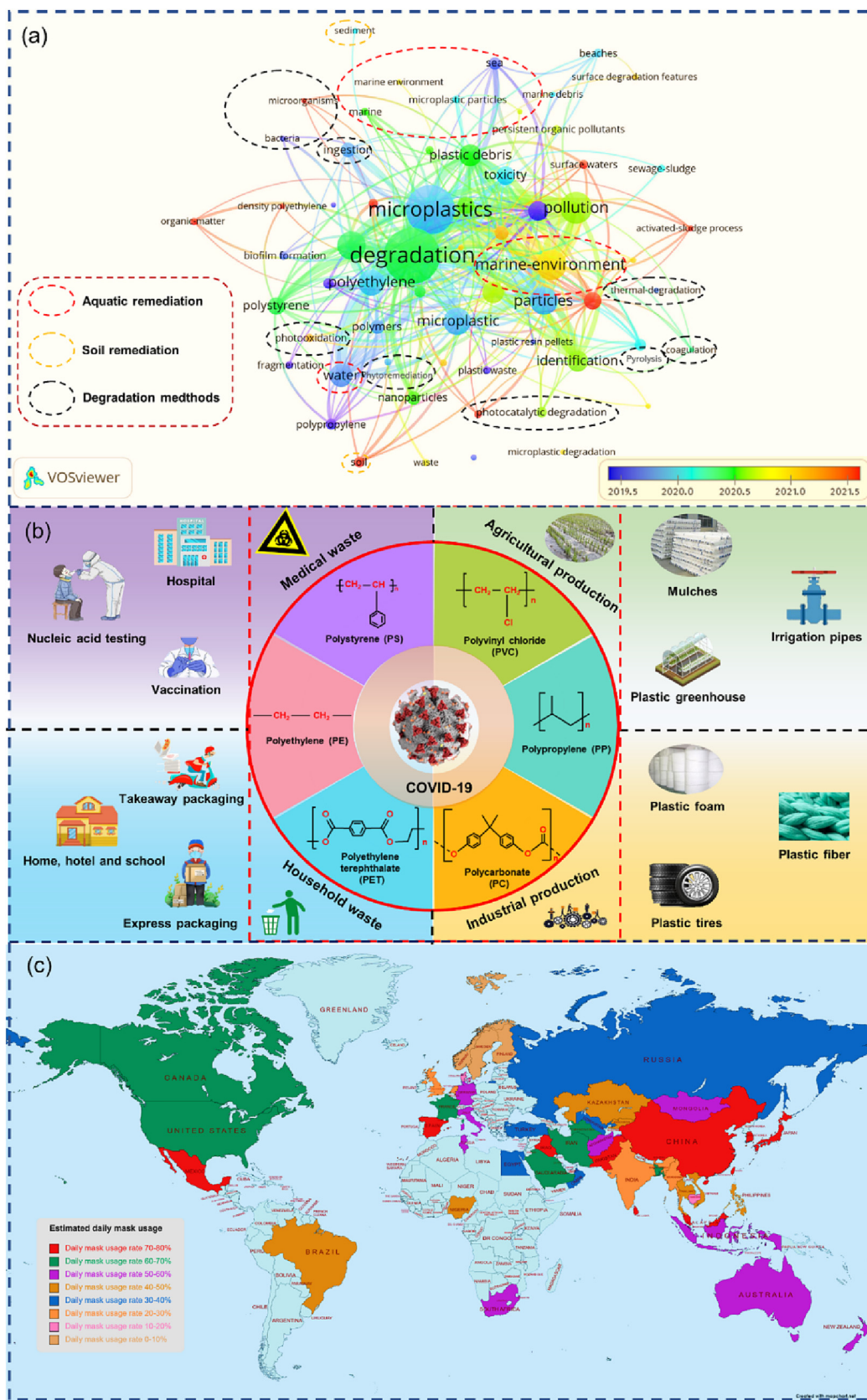


Fig. 1. (a) Based on the Web of Science search of 255 references on the keyword “microplastic degradation technology” in the last 3 years, and then using the visualization software VOSviewer to analyze the entries; (b) major sources of MPs generated during the COVID-19 pandemic; (c) estimated daily mask use in selected representative countries. Map created with mapchart.net© (Data from (Mahmoudnia et al., 2022; Sangkham, 2020).

2.3. Agricultural production

Plastic materials have become a crucial component of modern agricultural production, playing significant roles in crop protection and shade, soil cover, irrigation pipes, silage cover, plastic greenhouses, fruit protection film, and plastic-coated products, as well as packaging supplies for pesticides and fertilizers (Lamont, 2005; Mühlaupt, 2013). However, these plastics also contribute to the growing pool of MPs in agricultural soils. The use of plastic films and pesticides on agricultural soils has been linked to the accumulation of plastic debris and pesticide residues, resulting in decreased enzyme activity and microbial diversity, as well as losses of soil microbial carbon and nitrogen (Liu et al., 2019). Furthermore, the plastic debris in the soil can interact with microbial pathogens, heavy metals, and persistent organic pollutants on their surfaces, increasing the risk of environmental toxicity (Khalid et al., 2023). The uptake and accumulation of MPs by crops can contaminate the food chain and pose a significant threat to human health (Jiang et al., 2022). Additionally, plastic contamination in agricultural fields can arise from compost applications, which can transfer harmful contaminants such as di(ethylhexyl) phthalate and acetyl tributyl citrate to the soil, leading to compound contamination (Scopetani et al., 2022).

2.4. Industrial production

The utilization of raw materials, including vinyl hydrochloride and benzene, in the production of plastics poses a toxicological risk. The non-biodegradable nature of industrial plastics leads to soil, water, and air pollution, with rivers and landfills serving as hotspots for such waste (Shah et al., 2021). The industrial consumption of plastics is dominated by thermoplastics, which account for around 80 % of the total usage. PET is one such thermoplastic that is utilized for clothing fibers, as well as beverage and food packaging. Long-term infrastructure applications, such as pipes, cable coatings, and structural materials, account for 20–25 % of plastic usage, while the remainder is used for electronics, furniture, vehicles, and tires (Kazemi et al., 2021). In the insulation market, plastic foams and inorganic fibers, such as glass and mineral wool, are prevalent, with foams commonly used for sound-absorbing and insulating purposes in industrial and construction applications (Caniato et al., 2022). PVC resins and their compounds are highly versatile materials, with a range of applications that include flexible packaging, as well as the production of rigid construction products such as extruded tubes, profiles, and injection-molded electrical/sanitary fittings (Correa et al., 2019).

3. Migration and transformation of MPs in soil

The extant literature on MPs migration in soil tends to emphasize influencing factors over migration mechanisms. In view of this limitation, the present subsection expounds upon the migration and transformation mechanisms of MPs, with further elaboration on the influencing factors in soil. Fig. 2 offers a graphical representation of the migration and transformation mechanism, as well as the influencing factors, associated with MPs in soil.

3.1. Migration of MPs in the soil

3.1.1. Migration mechanisms of MPs in the soil

The complexity of MPs migration in soil and sediment demands further investigation to reveal their underlying mechanisms. Laermanns et al. (2021) conducted laboratory experiments to track the real-time surface migration of fluorescent and irregularly shaped MPs particles. Their findings indicated that the interaction of MPs with microreliefs hindered their migration, whereas preferential flow channels through large reliefs enhanced it. However, this work only explored horizontal migration, and the vertical migration mechanism still requires further investigation. Wu et al. (2021) studied the migration and retention mechanisms of MPs particles under unsaturated conditions using microfluidic experiments, but they did not

account for the role of the environment in MPs migration. Thus, Yu and Flury (2021) discussed the colloidal migration mechanisms of environmentally relevant MPs and NPs in soil. They emphasized that MPs and NPs migration in soil is influenced by their colloidal and surface properties, which depend on intrinsic properties such as plastic shape and size, and environmental factors like weathering, water flow, and bioturbation. While the laboratory-scale studies produced favorable results, it is imperative to investigate the interaction of MPs and NPs with the actual soil environment to fully comprehend their migration mechanisms.

3.1.2. Factors affecting the migration of MPs in the soil

As plastics enter the environment, they decompose via biotic or abiotic weathering into MPs, which can further decompose into NPs. Due to their high mobility and reactivity, MPs can easily travel through the air and contaminate the soil (Huang et al., 2022). The loose porosity of soil and the non-degradable nature of MPs provide good conditions for the migration of MPs in the soil environment. MPs migration in soil is a complex process that mainly involves vertical and horizontal migration, which is influenced by both biotic and abiotic factors (Zhou et al., 2020). Among them, biotic factors include soil fauna, soil microorganisms, plant roots, etc., while abiotic factors include soil physicochemical properties (soil pore space, fractures, soil texture, soil pH, organic matter and minerals, etc.), leaching, wet and dry cycles, wind action, surface runoff, agricultural tillage, and microplastic properties (size, shape, density, charge and surface chemistry) (Guo et al., 2020; Huang et al., 2022; Zhao et al., 2022). These factors influence the horizontal and vertical migration of MPs in soils to varying degrees. Nonetheless, the migration of MPs as contaminants in soil has received little attention, since aged MPs particles may adsorb various contaminants during migration, such as heavy metals, organic pollutants (Cao et al., 2021). The co-migration of MPs with adsorbed contaminants may cause complex contamination, which in turn poses a greater challenge to the remediation of soil environment. Therefore, conceptual migration models for MPs or in combination with other contaminants also need to be developed in the future to better characterize the migration behavior of MPs in soils (Ren et al., 2021).

3.2. Transformation of MPs in soil

In the soil environment, plastic debris is subject to physical, chemical, and biological transformations caused by mechanical abrasion, oxidation, and biological processes (Zhao et al., 2022). Physical transformations manifest as fragmentation and shrinkage of large plastic particles into smaller ones as a result of mechanical abrasion. Chemical transformations involve photodegradation, photo-oxidation, and thermal oxidation of MPs in the presence of UV light. These processes cause changes and reductions in the morphology and function of MPs. Microbial degradation, on the other hand, pertains to the conversion of plastic debris into polymers by biotic processes, which is subsequently followed by complete decomposition into CO₂, H₂O, and CH₄ through microbial mineralization. Among these processes, microbial degradation is considered to be the most effective form of biodegradation and could therefore be utilized for the remediation of MPs in the soil environment (Liu et al., 2022b; Maity et al., 2021; Sorasan et al., 2021).

4. Remediation technologies for MPs in soil

The present chapter delves into a comprehensive appraisal of four prevalent remediation technologies, with regard to the positioning of MPs contaminants across various depths in the soil. In particular, for the topmost layer of the soil, the use of pyrolysis or photocatalytic degradation is deemed an effective treatment method for MPs. On the other hand, phytoremediation appears to be a viable option for the shallow layer of the soil or in proximity to the plant roots. Furthermore, microbial degradation is proposed as an appropriate strategy for the sub-surface layer of the soil. Table 1 shows the advantages and drawbacks of the four remediation technologies and their principles.

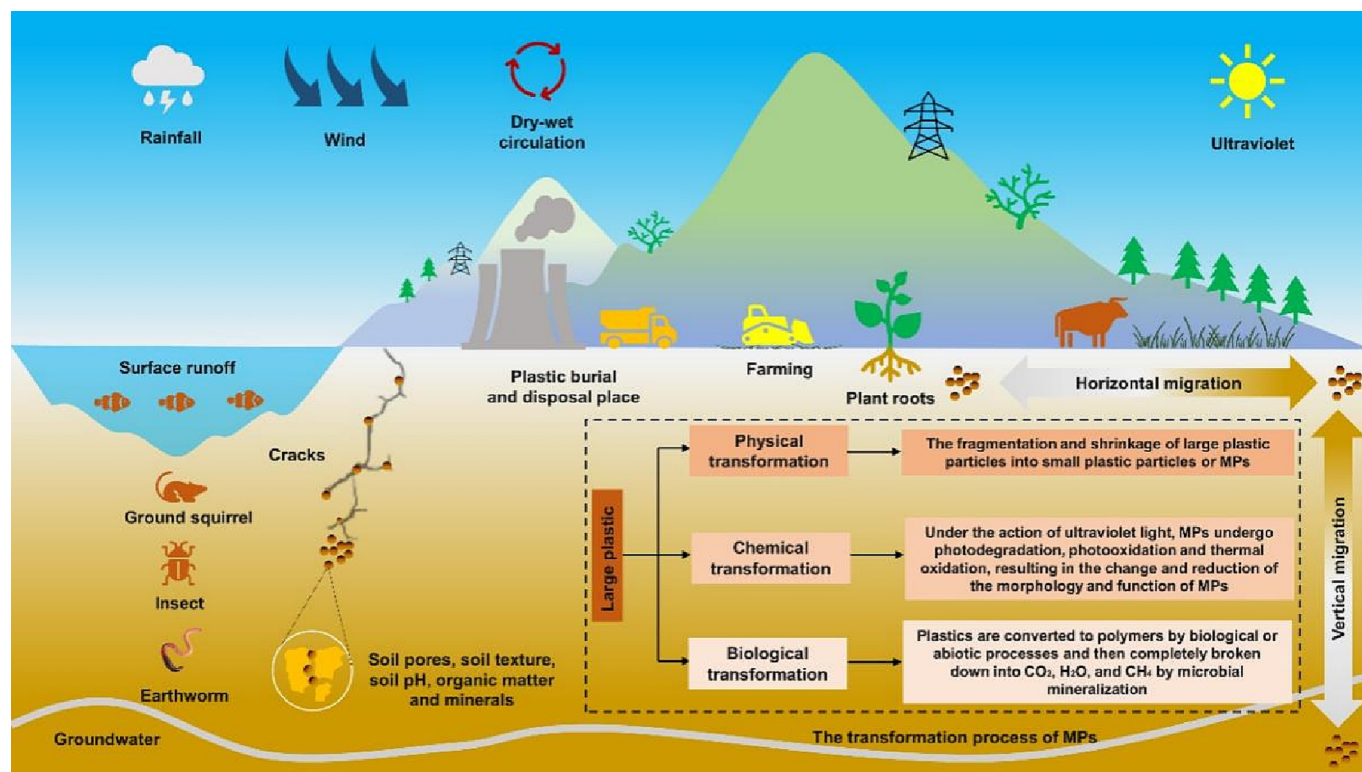


Fig. 2. Migration and transformation mechanism of MPs in the soil.

4.1. Thermal treatment technology

Thermal treatment involves heating the contaminated soil to high temperatures. It is widely used to remediate organic pollutants in soil, such as crude oil, agrochemicals, polychlorinated biphenyls, and polycyclic aromatic hydrocarbons (Zhao et al., 2019). Recently, Guo et al. (2021) found that thermal treatment did reduce the MPs in the soil. The results of this study indirectly suggest that thermal treatment is a new potential technology for remediation of soil MPs in the future. Besides, thermal treatment is effective in removing MPs from soil amended with sludge, where MPs were frequently reported (Elizalde-Velázquez and Gómez-Oliván, 2021; Fent, 1996). Thermal treatment of sludge can be achieved using various technologies, such as incineration, gasification, and pyrolysis (Cyzdik-Kwiatkowska et al., 2022). However, incineration generates nitrogen oxides, which can cause secondary pollution and require additional cost to control pollution (Skalska et al., 2010). Gasification, on the other hand, has shown limited success in Germany with regards to continuous

operation (Schnell et al., 2020). Pyrolysis, a thermochemical treatment technology for waste plastics, has been proven to be an environmentally friendly option (Uzoejinwa et al., 2018). Therefore, this section focuses on exploring pyrolysis technology as a viable option for the thermal treatment of soil to eliminate MPs.

4.1.1. Mechanism of pyrolysis of plastics

The process of pyrolysis involves the thermal degradation of long-chain polymer molecules into simpler, smaller molecules via the application of heat and pressure. Pyrolysis has been shown to be highly effective for treating plastic waste that is dispersed on soil surfaces (Yansaneh and Zein, 2022). This is due to the fact that pyrolysis does not introduce additional air or oxygen to the heating process. Additionally, the process parameters of pyrolysis, including feedstock, reaction time, temperature, and catalyst, can be manipulated to optimize product yields. The resulting products of pyrolysis do not require reprocessing and do not contribute to water pollution. Pyrolysis is also a convenient and flexible process that can reduce

Table 1

A summary of the advantages and disadvantages of the four remediation technologies and their principles.

Technology	Mechanism	Advantages	Drawbacks	References
Pyrolysis	Pyrolysis is a thermochemical method of thermally degrading long chain polymer molecules into smaller, simpler molecules by heat and pressure	The products of pyrolysis do not require further treatment and do not cause water pollution. Easy and flexible handling process, saving labor costs	High temperature conditions required	(Yansaneh and Zein, 2022) (Anuar Sharuddin et al., 2016) (Ni et al., 2020)
Phytoremediation	Phytoextraction; phytostabilization; phytofiltration	Environmentally friendly	Plant species and their growing needs need to be considered; longer remediation cycle	(Singh et al., 2022) (Sarwar et al., 2017) (Ting et al., 2018)
Microbial degradation	Biodegradation, biofragmentation, assimilation and mineralization	Affordable and environmentally friendly	It is difficult to identify and isolate highly active and functional enzymes	(Yuan et al., 2020) (Tiwari et al., 2020)
Photodegradation	Single linear oxygen-induced oxidation; free radical-induced oxidation	The sunlight used is a renewable resource; efficient and environmentally friendly	VOCs may be generated after photodegradation, causing secondary pollution	(Lee and Li, 2021) (Wu et al., 2022) (Dong et al., 2015)

labor costs. This process is suitable for most types of plastic waste, including PET, HDPE, LDPE, PP, and PS. However, it is not recommended for PVC due to the potential degradation of liquid oil quality and the toxic environmental impacts it may cause (Anuar Sharuddin et al., 2016).

The efficacy of pyrolysis technology surpasses that of conventional waste disposal methods such as landfills and incineration owing to its ability to recuperate valuable resources. Pyrolysis can effectively transform both recyclable and non-recyclable plastics into a synthetic gas, which can subsequently be employed to generate electricity or refined into liquid fuels, such as ethanol, hydrogen, and methanol. Further refinement of hydrogen and methanol can lead to the production of synthetic crude oil, diesel, and kerosene, while concentrated oil can serve as a valuable feedstock for the manufacture of fuels or specialty chemicals. This possibility of deriving energy from plastic waste provides an attractive solution to meet the ever-increasing energy demands (Pyrolysisadvocacy, 2020). A schematic representation of the pyrolysis process is shown in Fig. 3.

4.1.2. Application of pyrolysis plastics

In recent years, numerous studies have focused on the pyrolysis of MPs. The sewage sludge is one of the major sources of MPs in soil environments. Researchers have investigated the impact of temperature on pyrolytic MPs, and Ni et al. (2020) found that raising the pyrolysis temperature to 500 °C completely eliminated MPs residues in the sludge. This study suggests that pyrolysis is an effective measure for removing MPs from sewage sludge, however, incomplete pyrolysis at low temperatures may lead to residues that can adsorb other contaminants. The key challenge of pyrolysis is the requirement for high temperatures to achieve complete decomposition. Catalysts offer a solution to this issue, with catalytic pyrolysis being more efficient than conventional pyrolysis in terms of lower temperature requirements, cost savings, and improved product selectivity (Zhang et al., 2021). Temperature, catalytic time, raw material composition, and catalyst type are factors that affect catalytic pyrolysis, with solid acid catalysts, such as zeolite and silica-alumina, and bifunctional catalysts being the most commonly used types (Miandad et al., 2016; Yansaneh and Zein, 2022). While these factors have yielded good results, challenges related to

economic efficiency, environmental impact, and sustainability persist. Additionally, the different sizes of the feed and the problem of inappropriate mixing remain significant challenges for conventional pyrolysis. To address these issues, microwave-assisted pyrolysis has emerged, allowing for the uniform heating of large particle size feeds and reducing the need for external heat sources, resulting in improved product yield and reduced waste generation. The efficiency of microwave pyrolysis is influenced by temperature, reaction time, particle size, microwave power, and catalyst (Suresh et al., 2021).

Co-pyrolysis, which involves the simultaneous pyrolysis of two or more substances, has gained considerable research attention in recent times. An instance of this is the investigation carried out by Li et al. (2021) who employed thermogravimetric mass spectrometry infrared coupling to examine the product distribution during the co-pyrolysis of waste tires and waste plastics. This study has contributed significantly to the fundamental understanding of polymer pyrolysis. However, the pyrolysis process generates H_2 , CH_4 , NH_3 , CO/C_2H_4 , CO_2 , and aromatics, which require further treatment to mitigate their harmful effects. Similarly, Venturelli et al. (2022) also explored the pyrolysis of plastic residues and end-of-life tires and proffered the use of gases and fuel oil generated from the pyrolysis process to generate heat and electricity. This approach represents a typical case of circular economy and could serve as a feasible treatment measure for the post-pyrolysis products.

4.2. Phytoremediation technology

4.2.1. Phytoremediation mechanisms

Phytoremediation is a green technology that employs the natural processes of plants to remediate soils, sediments, and water contaminated with heavy metals, organic matter, and radionuclides (Singh et al., 2022). Despite the persistent nature of MPs in soil, Gong et al. (2023) considered phytoremediation as a potential in-situ remediation method for MPs contaminated soils. The mechanisms, influencing factors, and potential of this technology are comprehensively outlined. The potential phytoremediation techniques that could be useful for remediating MPs-contaminated soil or water include

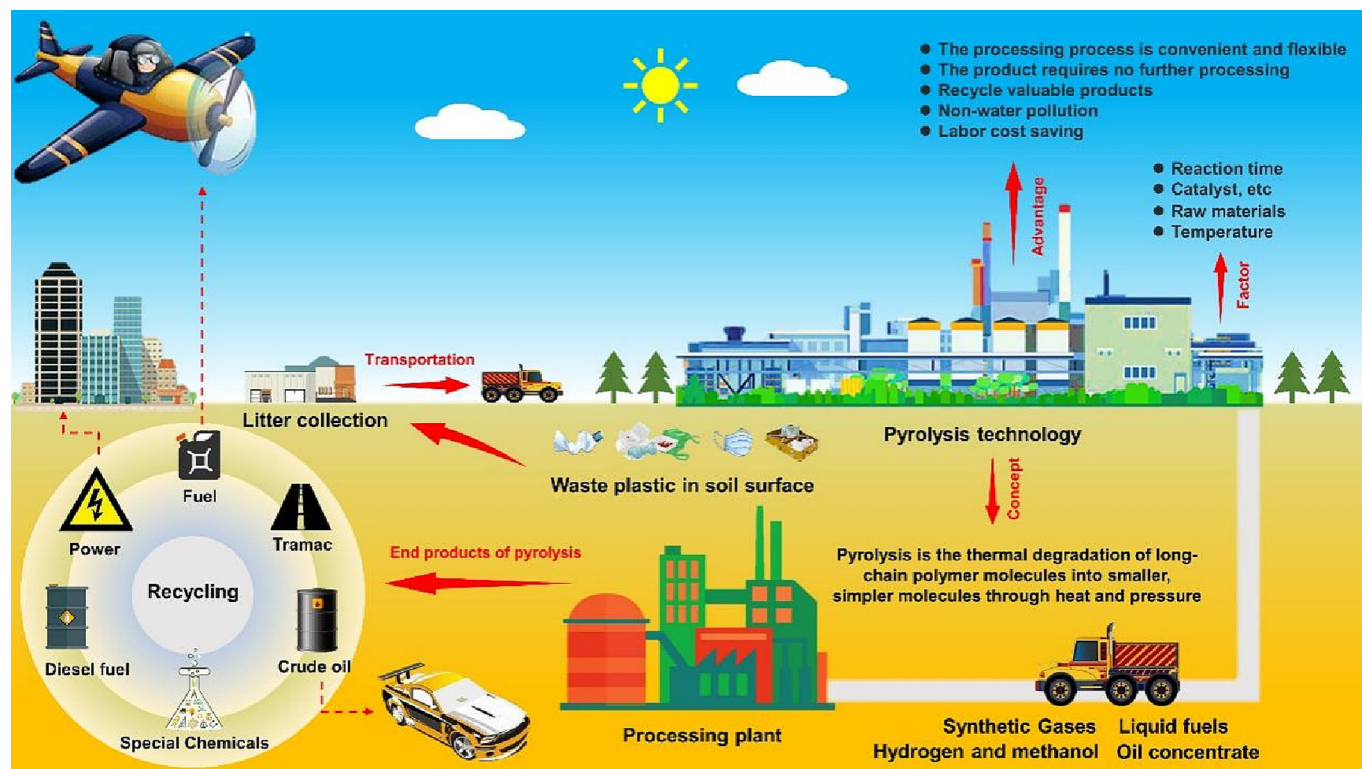


Fig. 3. The mechanisms of pyrolysis plastics.

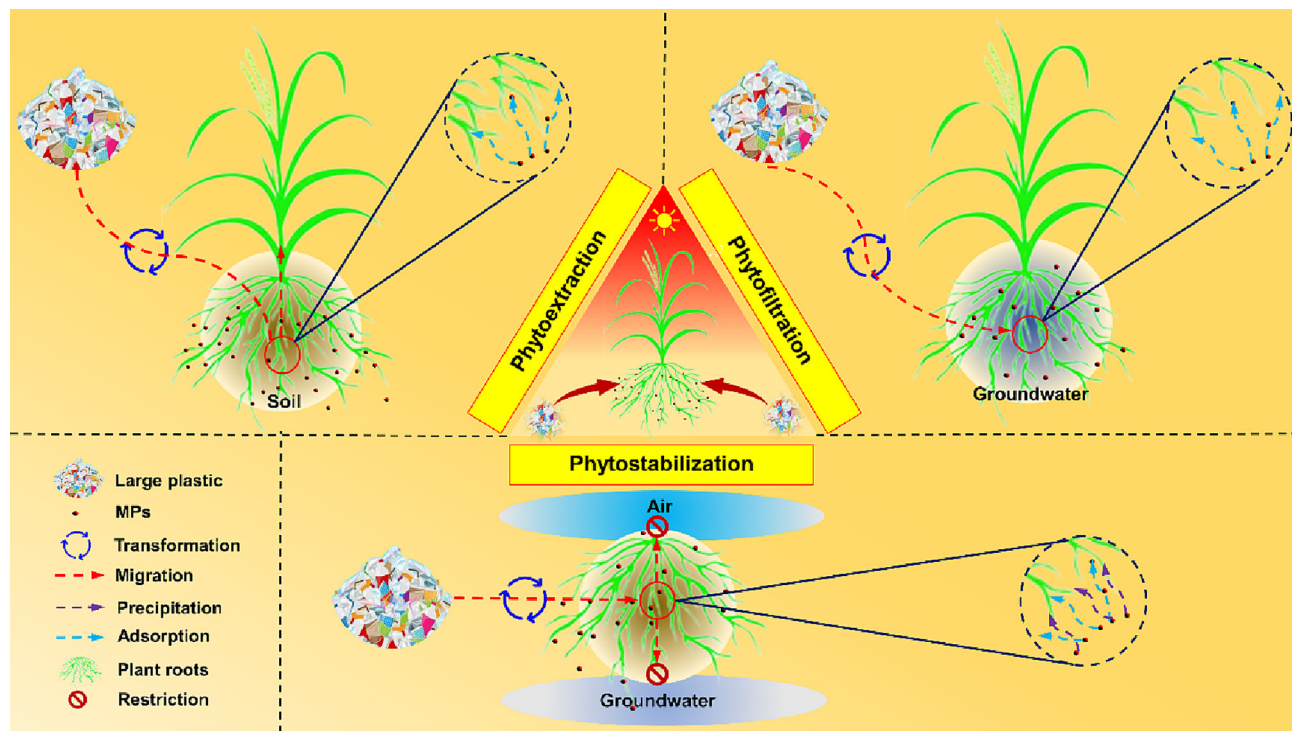


Fig. 4. Mechanisms of phytoremediation of MPs.

phytoextraction (phytoaccumulation), phytostabilization, and phytofiltration, as illustrated in Fig. 4.

Phytoremediation mechanisms encompass three main processes: (i) phytoextraction or phytoaccumulation, which involves the uptake of MPs contaminants by the roots of the plant and subsequent translocation to the above-ground tissue of the plant root system; (ii) phytostabilization, where the MPs pollutants are either absorbed and accumulated in the roots or precipitated in the inter-root zone, thereby preventing further contamination of groundwater or air; and (iii) phytofiltration, which entails the use of plant roots or seedlings to uptake or adsorb MPs from wastewater and groundwater streams, rather than from the soil (Ebere et al., 2019; Gong et al., 2023; Pidlisnyuk et al., 2021).

In addition to the remediation technique, plant species selection and their growth requirements are crucial factors to consider when employing phytoremediation to treat soil contaminants. High contamination levels may negatively impact plant growth, thereby limiting the effectiveness of phytoremediation (Sarwar et al., 2017). Phytoremediation is a suitable method for remediating sites with low biomass and economic value, making it an environmentally friendly approach. However, the technology's protracted remediation period and slow effects are significant drawbacks (Ting et al., 2018). Contaminant levels in plants must be monitored after translocation from soil to the root system, and when the levels exceed the plant's maximum tolerance limits, rational treatment of plants must be undertaken to prevent further harm to the environment, flora, and fauna (Paz-Alberto and Sigua, 2013).

4.2.2. Application of phytoremediation of MPs

The use of phytoremediation of MPs in the soil environment is currently in its infancy. Recent studies have explored the phytoremediation potential of different plant species and the influence of planting methods on the effectiveness of the technology. Austen et al. (2022) investigated the phytoremediation potential of birch for MPs in contaminated soils, highlighting the potential of this plant species in phytoremediation. Furthermore, it has been observed that intercropping or monocropping can significantly reduce the concentration of contaminants in the soil. For example, Ma et al. (2012) reported a reduction in the concentration of

phthalates (PAE) in soils by intercropping or monocropping with different plant species. The difference was that intercropping increased the biomass and functional diversity of soil microorganisms, and the amount of PAE absorbed by different plant species varied. Recently, Song et al. (2020) reported the potential of microorganisms (e.g., rhizobacteria and endophytes) to stimulate plant growth and enhance phytoremediation efficiency. However, the adaptation mechanisms of microorganisms and their compatibility with native microbial communities need to be fully understood, and the effectiveness of this synergistic remediation needs to be evaluated under different soil conditions. Therefore, future studies are required to assess the compatibility between native microbial communities and exotic strains to improve the efficiency of phytoremediation.

4.3. Microbial degradation technology

4.3.1. Microbial degradation mechanism

MPs are known to persist in the environment for extended periods. However, certain microorganisms can degrade MPs, such as bacteria, fungi, bacterial communities, and biofilms. Microbial degradation is a cost-effective and environmentally friendly technology for remediating MPs (Yuan et al., 2020). Fig. 5 illustrates the involvement of microorganisms in a series of physicochemical and biological reactions during the degradation process, including biodegradation, biofragmentation, assimilation, and mineralization (Tiwari et al., 2020). The degradation of large particle MPs requires two mechanisms: intracellular and extracellular degradation, as microorganisms do not easily degrade large particle MPs (Bacha et al., 2021; Yuan et al., 2022). Intracellular degradation refers to microorganisms accumulating on the surface of MPs and hydrolyzing them into short chains. In extracellular degradation, bacteria secrete extracellular enzymes, such as hydrolases, which degrade complex polymers of MPs into monomers. These short chains are then converted into end products (e.g. CO_2 , H_2O or CH_4) through different metabolic pathways during mineralization, ultimately undergoing biological natural attenuation (Malik et al., 2020; Miri et al., 2022). The degradation efficacy of microorganisms is influenced by the chemical structure and inherent properties of MPs, as well as biological and environmental factors. The degradation mechanism of each reaction is complex (Luo et al., 2022).

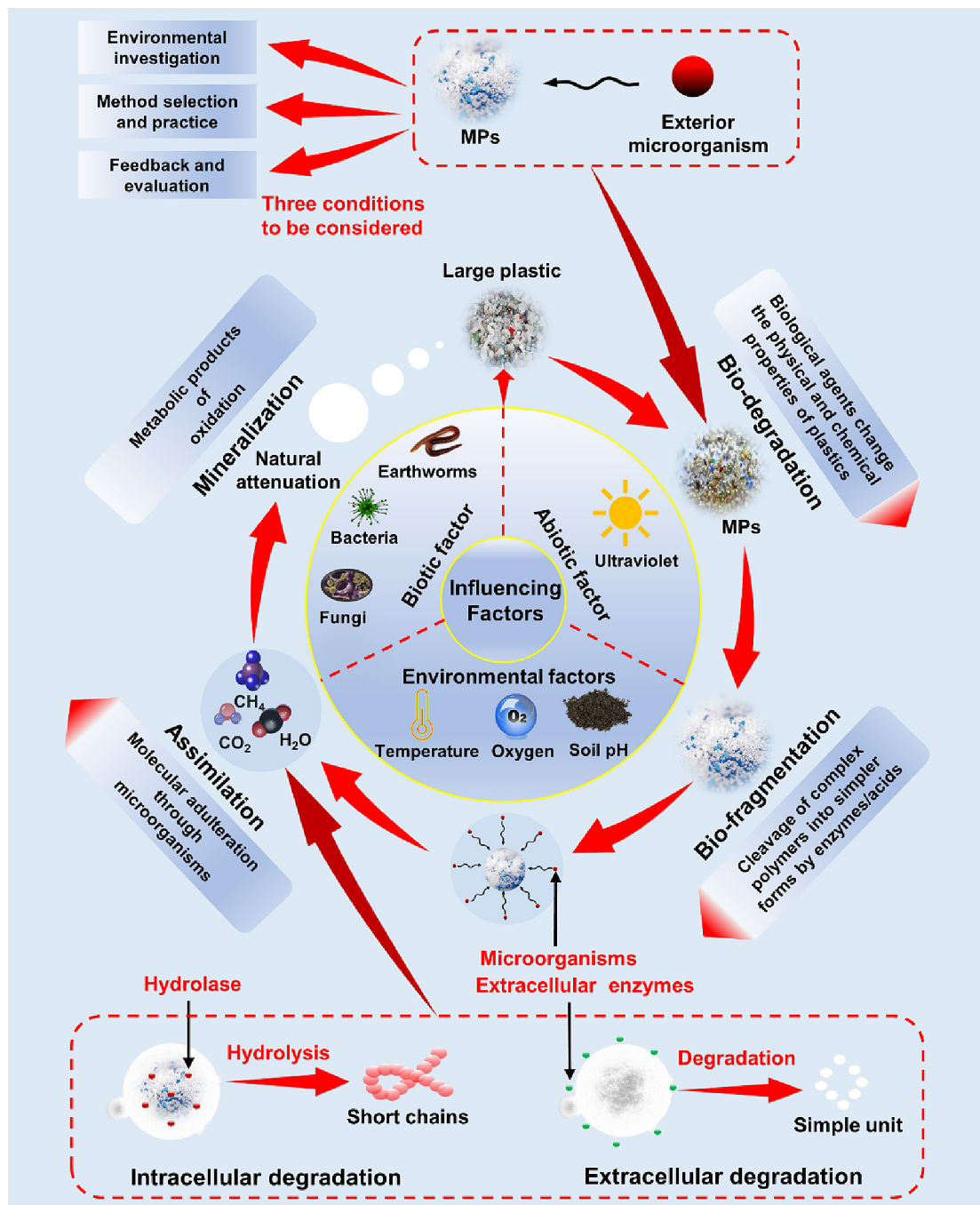


Fig. 5. The mechanisms of microbial degradation of MPs.

4.3.2. Application of microbial degradation MPs

The potential of microbial remediation as a viable technology for the remediation of MPs has been widely recognized owing to its unique properties (Bhatt et al., 2021). Bioremediation, which can be accomplished by microbial communities, bacteria or fungi, as well as various enzymes, represents a promising avenue in this regard (Othman et al., 2021). For instance, Auta et al. (2022) conducted in-situ remediation of mangrove soils contaminated with MPs using microflora in the soil. The results indicated a substantial reduction in the weight of MPs at different levels following a 90-day experimental period, with approximately 18 % of the remediated sites demonstrating a reduction in MPs weight. Similarly, Kowalczyk et al. (2016) employed a novel xylose-oxidizing colorless bacterium to facilitate the biodegradation of HDPE in soil, and found that the mass of HDPE was reduced and the bacteria grew normally, implying that xylose-

oxidizing peroxidase is a promising organism for future HDPE biodegradation studies. Moreover, Tiwari et al. (2022) employed *Brevibacillus brevis* (*B. brevis*) isolated from soil to remediate nylon 6,6 NMPs via shake flask experiments. It was observed that a weight loss of 22 w/w% of NMPs was achieved after 35 days of incubation with *B. brevis*, with accompanying changes in bacterial shape, suggesting that microbial degradation of NMPs through *B. brevis* induction is a promising technology.

The review by Ekanayaka et al. (2022) provides a comprehensive analysis of the role of fungi in the degradation of MPs, with Table 2 highlighting the various types of fungi used in recent years for the remediation of MPs in soil. Fungi exhibit high potential for microplastic degradation due to their diverse and efficient enzymatic systems. These enzymes, both extracellular and intracellular, can break down plastic polymers into monomers, resulting in the production of CO₂ and H₂O under aerobic conditions, and CH₄

Table 2

A selection of recent literature related to fungal types for remediation of different MPs in the soil environment.

Fungus name	MPs	Remediation effect	References
Aspergillus Niger	LDPE	Subject to natural climatic and environmental factors, Niger will allow significant cost reductions and will improve the biodegradability of LDPE	(Shabani et al., 2015)
Trichoderma spp. and Aspergillus norvegicus	LDPE	After 45 days of incubation, the isolates Trichoderma spp. and Aspergillus norvegicus reduced the weight of the LDPE films by 5.13 % and 6.63 %, respectively. Each isolate reduced the weight by 58 % and 40 %, respectively	(Munir et al., 2018)
Aspergillus terreus and Aspergillus sydowii	PE	Aspergillus terreus strain MANGF1/WL (over 50.00 ± 4 % WL, pH 9.5) and Aspergillus sydowii strain PNPF15/TS (TS loss 94.44 ± 2.40 %, pH 3.5) were the most effective and superior polyethylene degrading fungi	(Sangale et al., 2019)
Aspergillus tubingensis	PU	After two months in the liquid medium, the PU film was completely degraded into small pieces	(Khan et al., 2017)

PE: Polyethylene; PU: Polyurethane. The above content is adapted from (Ekanayaka et al., 2022).

under anaerobic conditions. Furthermore, fungi secrete hydrophobic proteins, which enhance substrate mobility and bioavailability, playing a crucial role in microbial remediation (Solanki et al., 2022). Although bacteria and fungi can degrade plastics, complete mineralization remains a challenge, and knowledge of the enzymes involved remains limited (Bacha et al., 2023).

4.4. Photodegradation technology

4.4.1. Photodegradation degradation of MPs

Photodegradation, driven by UV irradiation, is a crucial mechanism for the molecular breakage and cross-linking reactions of polymers, leading to the destruction of plastics (Liu et al., 2022a; Masry et al., 2021). The degradation of plastics in the environment is a complex process, resulting in the formation of new nonpolymers, oxidized polymers, hydrocarbon polymers, and low molecular weight substances. In their review, Lee and Li et al. (2021) discussed two principal photodegradation mechanisms: (i) oxidation induced by singlet oxygen (Fig. 6a); and (ii) oxidation induced by free radicals (Fig. 6b). The degradation of MPs during photodegradation in soil involves changes in both plastic morphology (such as the appearance of cracks and wrinkles) and functional group changes (such as loss of chemical bonds and the appearance of new functional groups). The photodegradation rate of MPs is strongly correlated with the clay content and the presence of iron oxide (needle iron ore and hematite) in soil. Needle iron ore, in particular, plays a significant role in the hydroxyl radical-mediated degradation of MPs. Conversely, the presence of organic carbon in soil can inhibit the photodegradation of MPs by chelating and hydrogen bonding to MPs, thereby reducing photolysis. Additionally, electrostatic interactions may play a significant role in determining the rate of photodegradation of MPs (Ding et al., 2022a; Ding et al., 2022b). While photodegradation can reduce the pollution caused by MPs to some extent, it can lead to secondary pollution of the soil environment by the release of toxic volatile organic compounds (VOCs), such as benzene, toluene, and phenol (Wu et al., 2022). Thus, controlling the elimination of VOCs from the air is crucial to reduce the costs of secondary pollution control.

4.4.2. Photocatalytic degradation of MPs

Photocatalytic degradation has been identified as an effective and environmentally friendly method for purifying plastic debris that is scattered on soil surfaces (Dong et al., 2015). However, once the plastic fragments are buried in soil and deprived of light, the degradation process may cease. Photocatalytic degradation utilizes a photochemical reaction process that mimics sunlight, thereby significantly accelerating the degradation rate. The degradation process involves the generation of a pair of electrons and holes in a redox reaction, ultimately resulting in the degradation of MPs to smaller inorganic molecules such as CO₂ and H₂O. An ideal photocatalyst for this process should be capable of light absorption at room temperature, exhibit high stability to photocorrosion, and be non-toxic (Chen et al., 2022; Lee and Li, 2021). TiO₂ is the most commonly used photocatalyst, which works primarily under UV light and has demonstrated its effectiveness as a safe and inert photocatalytic material in the oxidation of pollutants (Xing et al., 2018; Zhang et al., 2009). Photocatalytic degradation of MPs involves three main steps, namely, light absorption, separation and migration of photogenerated electrons and holes, and

redox reaction on the surface of the photocatalyst (Pham et al., 2021). As shown in Fig. 6c and Fig. 6d, Nabi et al. (2021) provided a comprehensive review of the general photocatalytic mechanism and the overall catalytic mechanism of TiO₂ under light illumination.

The degradation of MPs through photocatalytic processes is affected by several physicochemical factors such as the properties of MPs, the quantity and type of photocatalysts, light source, oxygen concentration, humidity, pH, and temperature. The activity of photocatalysts is significantly influenced by light source and humidity, while an excess of oxygen accelerates the degradation of MPs (Ge et al., 2022). Different catalytic materials including pure, modified, doped, and nano TiO₂ have shown varying roles in the photodegradation of MPs (Ge et al., 2022; Nabi et al., 2020). Besides TiO₂, ZnO, CeO₂, Fe₂O₃ and CdS have also been used as photocatalysts. In particular, ZnO has emerged as a frequently used substitute for TiO₂, owing to its high photocatalytic degradation rates (Ghosh et al., 2019; Pradhan and Parida, 2010). Despite the benefits of photocatalytic degradation, it is imperative to address the environmental impacts of CO₂ generated from most photocatalysts (Lee and Li, 2021). Hence, developing new cost-effective and environmentally friendly catalysts is a crucial research area. Although numerous studies have focused on the photocatalytic degradation of MPs in marine and aqueous environments, research on MPs in the soil surface layer remains relatively scant (Ajith et al., 2020; Ebrahimbabaie et al., 2022). Future investigations must fill this gap and expand our understanding of photocatalytic degradation in different environments.

Significantly, the practicality of the four technologies discussed in this study has primarily been demonstrated through laboratory experiments or limited-scale implementations. To implement the proposed treatment technologies on a larger scale, several considerations need to be taken into account. Firstly, the phytoremediation technology is feasible for large-scale remediation due to its low cost and eco-friendliness. However, the selection of suitable plant species, climatic conditions, and soil type is critical to achieve effective remediation. Secondly, the thermal treatment technology requires high energy consumption and may not be suitable for large-scale application due to its high cost and potential environmental impact. Thirdly, microbial degradation technology has high potential for large-scale application due to its high efficiency and cost-effectiveness. However, the efficacy of microbial degradation is limited by environmental factors such as pH, temperature, and nutrient availability. Finally, photodegradation technology has high potential for large-scale application due to its non-invasive nature and low cost. However, its efficacy depends on factors such as light intensity, wavelength, and exposure time, which need to be carefully controlled. Overall, the feasibility of scaling up these technologies for larger-scale remediation depends on various factors such as cost-effectiveness, efficiency, and environmental impact, and careful evaluation of their limitations and challenges is necessary.

5. Prospects

The COVID-19 pandemic continues to have a significant impact on the world, with human life gradually returning to pre-pandemic norms. Despite this, the issue of plastic pollution remains a pressing concern and is potentially worsening. To address this, this section offers four perspectives on controlling the sources of MPs pollution, appropriate disposal of plastic waste, exploring alternative plastic supplies, and technologies for remediating

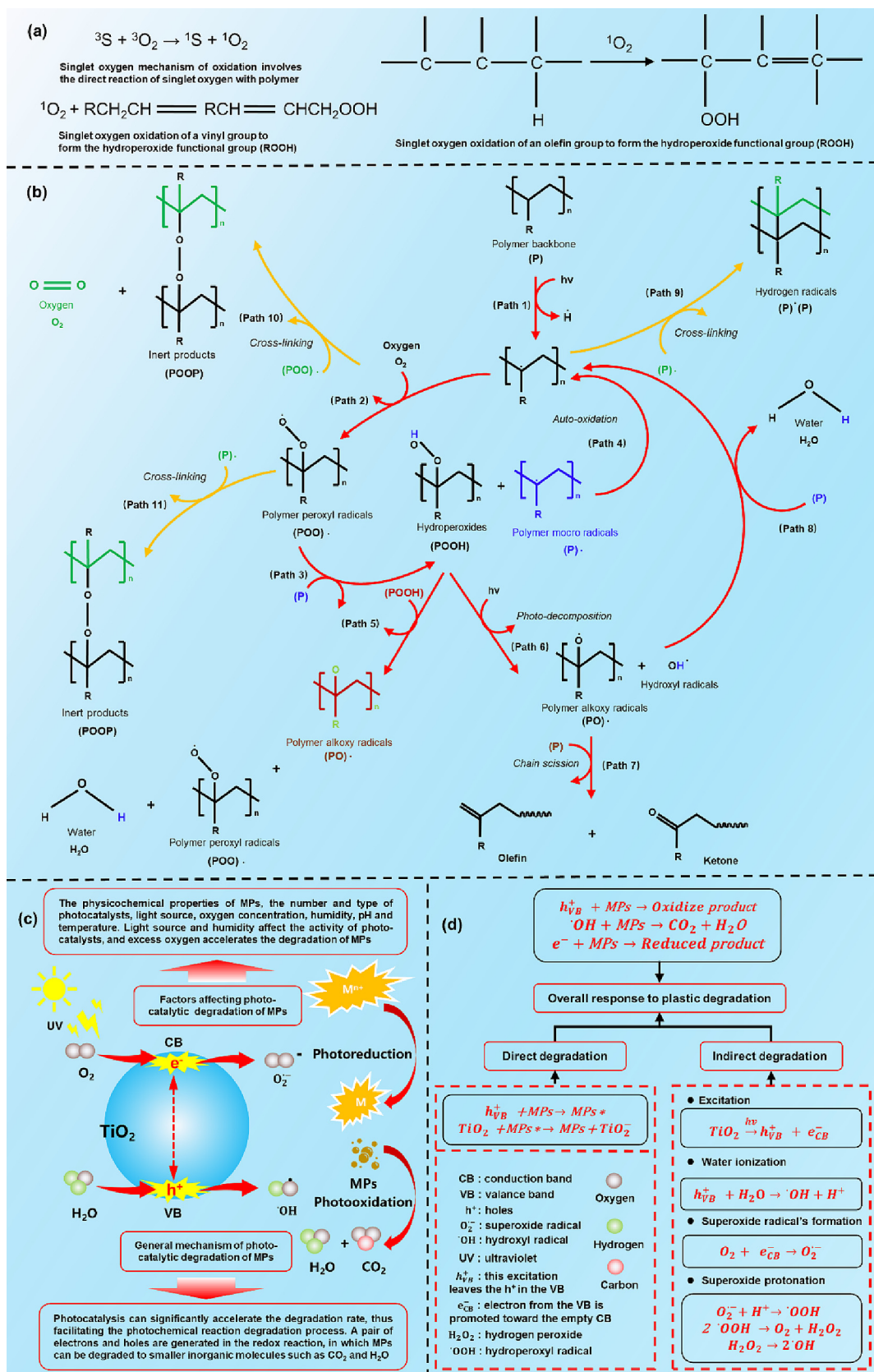


Fig. 6. Photodegradation mechanisms: (a) singlet oxygen mechanism of oxidation; (b) free radical mechanism of oxidation (Adapted from (Lee and Li, 2021)). Photocatalytic degradation mechanism: (c) general mechanism of photocatalytic degradation of MPs; (d) the overall mechanism of photocatalytic degradation (Adapted from (Nabi et al., 2021)).

soil contaminated with plastic waste. These perspectives aim to provide valuable references for future research on treating MPs in soil.

5.1. Enhance citizens' awareness of environmental protection

The utilization of plastic products in daily life is a significant source of MPs pollution, with citizens playing a crucial role in mitigating this problem. Hence, it is imperative to enhance the environmental consciousness of citizens. This includes but is not limited to: (i) reducing plastic usage by adopting alternatives like cloth bags for shopping, which can be reused multiple times; (ii) adhering to waste segregation standards, exemplified by cities like Shanghai in China and Singapore in the Asian region, where waste segregation is strictly enforced through legislative fines and publicity campaigns aimed at raising environmental awareness; (iii) promoting environmentally sustainable practices by creating incentive systems that reward households, businesses, factories, and individuals for adhering to environmental regulations while penalizing violators. Such measures can aid in curbing microplastic pollution and promoting environmental sustainability.

5.2. Improve plastic waste management and treatment capacity

The current waste management systems in most regions of the world, particularly in developing countries, are insufficient to manage the increasing amount of plastic waste. This could aggravate mismanagement and plastic leakage into the environment, leading to a potential environmental crisis. Therefore, it is crucial to implement immediate scientific sterilization and secure disposal of contaminated plastic waste in sealed bags to mitigate the risk of transmission to sanitation workers (Vanapalli et al., 2021). The pandemic has further exacerbated the waste disposal system's capacity to handle various types of food and plastic waste. Therefore, mandatory emergency treatment and disposal, such as co-disposal in municipal solid waste incinerators, cement kilns, industrial furnaces, and site landfills, are necessary to increase treatment capacity (Hantoko et al., 2021). Additionally, staff involved in waste management at each stage of waste generation, treatment, and storage, waste collection and transportation, or final disposal require enhanced training and education to improve their operational capabilities. This will contribute to the safe and effective handling of plastic waste final disposal.

5.3. Research and development of alternative plastic supplies

The ubiquitous use of traditional plastic products has led to their rampant pollution due to inadequate disposal, necessitating the development of alternative plastic supplies. Biodegradable plastics have emerged as a promising alternative to traditional, long-lasting plastics, providing an effective solution to the global plastic pollution problem. Biodegradation is achieved through microbial assimilation, wherein microorganisms break down carbon matrix plastic polymers into CO₂, CH₄, and microbial biomass, which can be utilized for energy and carbon assimilation (Flury and Narayan, 2021). Nonetheless, biodegradable plastics do not entirely address the issue of plastic waste accumulation in the environment. Thus, raising awareness regarding proper and controlled plastic management, disposal, and recycling practices is a crucial factor in preventing plastic pollution. Despite their high cost, the quality and eco-friendliness of biodegradable plastics render them a viable option for the future, provided that the public is made aware of their benefits (Di Bartolo et al., 2021; Filho et al., 2022; Haider et al., 2019).

5.4. Increase the development and application of remediation technologies

In the soil environment, a range of physical, chemical, and biological methods have been employed to degrade MPs. However, such strategies have limitations, including high remediation costs, secondary pollution, and environmental impact. For instance, microbial degradation through bacteria, fungi, and archaea has been shown to be challenging to identify

using traditional sequencing techniques due to culture technology limitations. Recently, the use of macrogenomic technology has been proposed to identify diverse microbial communities and dynamics in the environment, resulting in improved microbial degradation effectiveness (Gaur et al., 2022). Macrogeonomic approaches can identify non-cultured microorganisms, and assist in establishing function-based analyses, highlighting the importance of future studies in this area (Tiwareti et al., 2020). Such studies will substantially reduce MPs in the soil environment, resulting in an improved habitat for plant and animal growth.

6. Conclusion

This study presents an overview of the sources of plastic wastes generated during the COVID-19 pandemic, including those from medical, household, industrial, and agricultural production, which subsequently decompose into MPs through weather and mechanical degradation. The migration and transformation behavior of MPs in soil is also discussed, including their interactions with biotic and abiotic factors that could potentially harm soil properties, plant growth, and microbial communities. Additionally, four remediation methods for MPs in soil are presented, namely thermal treatment (pyrolysis), phytoremediation, microbial degradation, and photodegradation (photocatalytic degradation) technologies. While these methods show promise in treating MPs in soil, they are not without limitations. Thus, four perspectives are proposed, including the control of MPs pollution sources, rational disposal of plastic wastes, alternative plastic supplies, and technologies for remediating soil after contamination by plastic wastes, which may serve as a reference for future treatments of MPs in soil.

CRediT authorship contribution statement

Shan Zhao: Conceptualization, Writing – review & editing, Supervision. **Jian Zhang:** Writing – original draft, Data curation, Methodology.

Data availability

No data was used for the research described in the article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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