Bulletin of Pure and Applied Sciences
Zoology (Animal Science), Vol.43A, No.1,
January-June 2024: P.216-234

Print version ISSN 0970 0765
Online version ISSN 2320 3188
DOI: https://doi.org/10.52710/bpas-zoo.40

Review Article
Content Available online at: https://www.bpasjournals.com/

An Insight into the Toxicological Effects of Microplastics on Earthworms and Their Removal Technologies

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Received on 17.01.2024
Revised on 27.03.2024
Accepted on 07.04.2024

ABSTRACT:
The damaging effects of microplastics (MPs), which are ubiquitous environmental pollutants measuring smaller than 5 mm, on terrestrial ecosystems, particularly earthworms are a cause for worry. This review analyzes the sources, distribution, and fate of MPs in soils, emphasizing their ubiquitous presence. It delves into the toxicological impact on earthworms, covering exposure mechanisms and effects on physiology, biochemistry, reproduction, and soil ecosystems. The article also explores various removal technologies, including physical, chemical, phytoremediation, and microbial methods, to combat MPs contamination. Improved risk assessment, long-term studies, and regulatory frameworks are stressed for addressing this pollution. The review underscores the urgency of preserving earthworm populations and soil ecosystems through sustainable practices, urging collaborative efforts in tackling this global environmental challenge.

Keywords:
Microplastic; Earthworm; Polyethylene; Toxicology; Oxidative stress

How to cite this article: Sheoran G. and Shukla V. (2024). An Insight into the Toxicological Effects of Microplastics on Earthworms and Their Removal Technologies. *Bulletin of Pure and Applied Sciences-Zoology*, 43A (1), 216-234.

INTRODUCTION

The alarming rise in plastic pollution has become a noteworthy global environmental apprehension. Among, various forms of plastic debris, microplastics (MPs) have gathered considerable attention, due to their widespread presence in ecosystems, including soil (Sajjad et al., 2022). Microplastics are defined as plastic particles with dimensions less than 5 mm, encompassing both primary MPs (manufactured as small particles) and 2 º Microplastics (resulting from the division of large plastic items) (Y. Zhang et al., 2020). Their smaller size and persistence in the atmosphere have led to their ubiquity in terrestrial systems, raising concerns about their potential toxicological effects on organisms that inhabit these ecosystems (Campanale et al., 2022).

Earthworms, classified as oligochaetes, are an essential module of soil ecosystems, playing a fundamental part in soil health, nutrient cycle, and organic matter decomposition (Medina-Sauza et al., 2019). Their burrowing activities contribute to soil aeration and water infiltration, while their feeding habits facilitate the breakdown and incorporation of organic matter into the soil matrix. Furthermore, earthworms enhance soil fertility through the excretion of nutrient-rich castings, promoting plant growth and ecosystem productivity. Earthworms provide essential ecological functions; hence it is critical to comprehend how MPs affect these creatures (Ahmed & Al-Mutairi, 2022). The toxicological effects of MPs on earthworms have emerged as a topic of growing concern in recent years. Several studies have reported adverse effects of MPs exposure on earthworm physiology, behavior, reproduction, and overall fitness (Y. Liu, Xu, & Yu, 2022; Schöpfer et al., 2020; Xu & Yu, 2021). The potential pathways through which earthworms interact with MPs include ingestion, absorption through the skin, and physical entanglement. Once internalized, MPs can accumulate within earthworm tissues, potentially causing mechanical damage, hindered digestion, and interference with vital physiological processes (Roy, Dey, & Jamal, 2022).

Physical effects of MPs on earthworms include blockage or hindrance of the digestive system, leading to reduced feeding efficiency and nutrient uptake. The accumulation of MPs in earthworm tissues can also impede the movement of coelomic fluid, essential for maintaining physiological homeostasis (Ju, Yang, Osman, & Geissen, 2023). Furthermore, the presence of MPs may alter the burrowing behavior of earthworms, influencing soil structure and nutrient cycling dynamics. The potential consequences of MPs exposure extend beyond individual earthworms, potentially affecting population dynamics and overall ecosystem functioning (Bouaicha et al., 2022).

Not only physical cheracterstics, the chemical properties of MPs can also elicit toxicological effects on earthworms. Microplastics possess the ability to absorb and concentrate a range of organic contaminants found in the environment, including heavy metals, polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs), heavy metals (Joo, Liang, Kim, Byun, & Choi, 2021). When ingested by earthworms, these adsorbed contaminants can be released in the digestive tract, foremost to internal exposure and potential toxicity (Xiao et al., 2022). Additionally, MPs themselves may contain additives and plasticizers that can leach into the surrounding tissues, further exacerbating the toxicological effects on earthworms (Ockenden, Northcott, Tremblay, & Simon, 2022).

The potential implications of microplastic-induced toxicity on earthworms extend to the broader soil ecosystem. Earthworms are vital ecosystem engineers, contributing to soil structure, nutrient cycling, and overall soil health (Jouquet, Blanchart, & Capowiez, 2014). Their activities promote the development of stable soil aggregates, enhancing water infiltration and reducing erosion. Furthermore, earthworms facilitate the breakdown of organic matter, influencing the availability of nutrients to plants and promoting soil fertility (Ahmed & Al-Mutairi, 2022). According to Frisch et al. (2019), there might be a domino effect on soil health and ecosystem functioning from any disturbance to the earthworm population and their responsibilities.

Given the potential risks associated with MPs on earthworms and soil ecosystems, it is crucial to explore effective strategies for mitigating microplastic pollution. Various removal technologies have been developed to reduce microplastic contamination in soils, aiming to safeguard the health and functionality of earthworms and soil ecosystems. These technologies encompass physical removal methods, chemical remediation, phytoremediation, and microbial remediation (Jinrui Zhang et al., 2022).

This review provides a thorough analysis of the main sources, distribution, and fate of MPs in soils ecosystem, shedding light on their pervasive presence. The study delves into the toxicological impact of MPs on earthworms, encompassing exposure mechanisms and effects on various aspects of their physiology, biochemistry, reproduction, and soil ecosystems. Furthermore, this article explores and evaluates different removal technologies aimed at combating MPs contamination in soil. These methods include physical, chemical, phytoremediation, and microbial approaches, each with their own merits and challenges. To address the growing issue of MP pollution effectively, the review emphasizes the need for improved risk assessment, long-term studies, and the implementation of robust regulatory frameworks.

SOURCES RESPONSIBLE FOR SOIL MICROPLASTICS

There are significant differences in the distribution of MPs in soils based on geography and environment. Polypropylene, polyethylene, polyester, and polystyrene are often the main forms of polymers detected in soils, with small-sized MPs being more common (Iqbal et al., 2023). Microplastics come in a variety of shapes and sizes, including pellets, films, fibers, and pieces. However, due to the various sources of MPs that reach the soil environment, the precise shape and polymer composition of MPs vary from region to region (Duis & Coors, 2016). Because of the variety of plastic types and sizes and the lack of comprehensive information regarding soil degradation processes, it is challenging to set a realistic timescale for MP disintegration and the subsequent release of their components.

MPs frequently cause contamination of a extensive range of soil types used for different drives, such as agricultural, pasture, forest, industrial, and distant floodplain soils **(Figure 1)**. MP concentrations can rise to 6.7% of the soil weight in areas that are severely impacted by pollution. Plastics produced at the tiny level for both home and industrial purposes are referred to as primary microplastics (Büks & Kaupenjohann, 2020). Examples include fibers, films, seeds, powders, and pellets made of plastic that are found in children's products, personal care items like cleansers and face washes, and cosmetics like sunscreen. Primary MPs can also result from goods made by shipbreaking or from materials utilized in air-blasting technology. Larger plastic products, such as primary MPs, eventually break down physically, chemically, and biologically to produce secondary MPs (Lambert & Wagner, 2018; Szymańska & Obolewski, 2020).

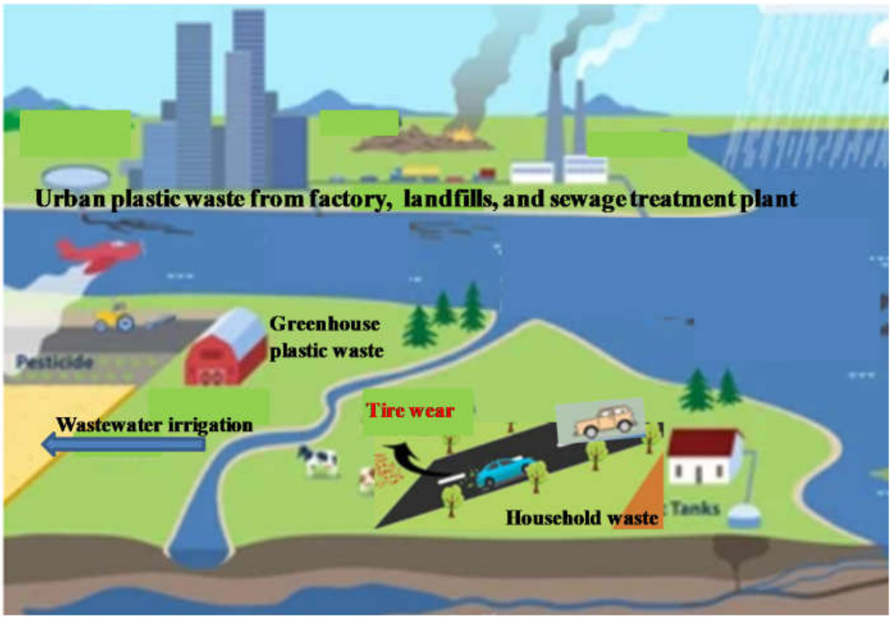

Figure 1: Different sources of microplastics in soil systems and their migration to agricultural soil through irrigation.

Microplastics (MPs) that mimic films are believed to be a common source in agricultural contexts. Inadequate disposal of agricultural plastic films can also result in the accumulation of MPs (Huang, Liu, Jia, Yan, & Wang, 2020). MPs from urban waste drains can be moved and dispersed by adding soil additives, such as compost and sludge, to rural areas. Inadvertent plastic trash can also add up to a substantial amount. Unexpectedly, MPs fibers can also be produced by washing machines, and these fibers could end up in fields via water treatment plants (Cesa, Turra, Checon, Leonardi, & Baruque-Ramos, 2020). And it's interesting to think about tumble dryers as potential MP sources.

Small particles or fibers that are released into the air from places such as surface dumps or landfills have the ability to go great distances in dispersal. Through atmospheric deposition, these airborne MPs can then be transferred to terrestrial systems including the soil (Haque & Fan, 2023). Earthworms in particular are geophagous soil creatures that may contribute to the development of secondary MPs. Earthworms have the ability to break up small plastic particles in their gizzards, which are then consumed and converted into MPs. Plastic particles put on the soil's surface may find their way into the soil through the burrows made by anecic earthworms, which dig vertical tunnels and feed mostly at the soil's surface (Dreibrodt et al., 2022).

Furthermore, inadequate management practices may leave a considerable quantity of plastic mulching residues in the soil, which could facilitate the accumulation of MPs in the soil due to physical erosion processes and UV radiation-induced soil degradation (Afrin, Uddin, & Rahman, 2020). In the natural environment, leftover plastic trash gradually breaks down into tiny pieces called microplastics (MPs). Numerous processes, including exposure to ultraviolet light, thermal oxidation, physical abrasion, and biodegradation, can lead to the destruction of microplastics (Chamas et al., 2020). MPs have alterations in their polymer's chemical structure during these degradation processes, such as disproportionate chain cleaving and a rise in functional groups that contain oxygen (Allayarov et al., 2020). Because of agricultural operations and sediment deposition, soil-bound MPs can move over small distances, as they can when plowing, demonstrating their mobility.

The process of bioturbation, which is the movement of soil particles by soil-dwelling organisms, has been found to affect MP mobility in the soil (Guo et al., 2020). MPs have been observed to be transferred from the topsoil to the lower soil layers by specific earthworm and collembolan species. Moreover, there is data that proposes soil erosion and runoff processes can transfer MPs over great distances. MPs may eventually find their way into the ocean as a result of this penetration into aquatic bodies (Rehm, Zeyer, Schmidt, & Fiener, 2021).

It has been found that microplastics exist in both deep sub-soils and top-soils. The topsoil offers a possible habitat for MP breakdown because of its unique qualities, which include direct exposure to UV light, somewhat higher temperatures, and greater oxygen availability (Rizzarelli, Rapisarda, Ascione, Innocenti, & La Mantia, 2021). However, the rate at which MPs degrade in soil is often sluggish and is dependent on a number of variables, such as microbial activity, animals that live in the soil, agricultural methods, and other processes (Uwamungu et al., 2022).

The physical characteristics of MPs, including as their mobility and routes, are also very important in deciding their fate and interactions with the environment. The behavior of MPs is generally influenced by hydrodynamic and atmospheric conditions (Sharma, Ma, Guo, & Zhang, 2021). Moreover, the sizes, densities, and morphologies of MP particles affect their dispersion, resuspension, and settling rates. The overall distribution and mobility of MPs within and outside of the soil are influenced by these combined variables (Shaoliang Zhang et al., 2021).

TOXICOLOGICAL EFFECTS OF MICROPLASTICS

Research on the toxicological impacts of MPs on earthworms is relatively scarce when compared to studies focused on marine organisms (Ribeiro, O'Brien, Galloway, & Thomas, 2019). Nevertheless, emerging evidence indicates that MPs can exert detrimental effects on earthworms, which play a vital role as soil-dwelling organisms essential for maintaining soil health and facilitating nutrient cycling (Cao et al., 2020).

Metabolic and trancriptomic changes

Ingestion and accumulation: Earthworms have the ability to consume MPs found in the soil, either directly or indirectly by consuming organic matter that is contaminated (Singh, Sharma, Khajuria, Singh, & Vig, 2020). Once ingested, MPs can gather and accumulate within the digestive tract of earthworms, potentially resulting in physical obstructions and hindering the absorption of nutrients **(Table 1)**. Multiple studies have verified that earthworms can ingest and accumulate MPs (Huerta Lwanga et al., 2017; Wang et al., 2019), leading to a reduction in their growth, reproduction rate, and lifespan (Kwak & An, 2021). The existence of MPs in the diet of earthworms can effect in gastrointestinal tissue damage and the dilution of food resources **(Figure 2)**. In a study conducted by (Tourinho et al. (2021), it was observed that earthworms exposed to MPs fibers exhibited an increase in lipid, protein, and carbohydrate content. The researchers specifically investigated the effects of silver exposure and attributed the rise in protein content to the binding of metal-associated proteins (Tourinho et al., 2021). This overall increase in metabolite concentration could potentially be attributed to immune-protection or a stress response (Rodriguez-Seijo et al., 2017). Chen and colleagues (2022) conducted a study to observe the effects of polyethylene and propylene MPs on the breakdown and transcriptomics of earthworms (J. Chen et al., 2022). Their findings revealed an elevation in the metabolisms of arachidonic acid and glycerol lipids, indicating a disruption in lipid metabolism. In a recent study conducted by Tang and colleagues (2023), the effects of polystyrene nano-plastics on earthworms were examined using advanced multi-omics tools. Their findings revealed an upregulation in the expression of digestive genes, as evidenced by transcriptomics analysis. Additionally, the researchers observed an increase in aldosterone-regulated sodium reabsorption at the transcriptome level and alterations in inositol phosphate metabolism at the proteomic level. Moreover, through transcriptional-metabolic analysis, disruptions in carbohydrate and arachidonic acid metabolisms were identified as responses to exposure to polystyrene nano-plastics. These results highlight the potential adverse effects of nano-plastic pollution on earthworm physiology and metabolism (Tang et al., 2023). In a separate investigation, Li et al. (2021) documented a substantial upregulation in the expression of 34,937 genes in response to exposure to high-density polyethylene MPs. Similarly, during exposure to polypropylene MPs, an increase in the expression of 28,494 genes was observed by the researchers (Li et al., 2021). In addition to the metabolic consequences observed in earthworms, MPs also have an impact on their reproductive health. Multiple studies have provided indication of the detrimental effects of MPs on the population size of subsequent generations of earthworms.

Table 1: Toxicological effect of microplastics on earthworms.

Sr. No.	Earthworm species and microplastic	Exposure of microplastic	Toxicological effect of microplastic	References
1.	*Eisenia fetida*; Polystyrene	Earthworms were exposed to 100 µg and 1000 µg of sized 100 nm and 1300 nm polystyrene microplastics per kg of artificial soil for 14 days.	Histopathological study revealed that the intestinal cells were damaged. Higher of MP induced oxidative stress which was confirmed by GSH and SOD levels. The comet assay indicated DNA damage in specimen due to exposure to MP.	(Jiang et al., 2020)
2.	*Eisenia andrei*; Polyethylene	Earthworms were exposed two size of polyethylene microplastic sphere (180PE and 250PE) at a concentration of 1000 mg/kg dry soil for 21 days.	Exposure to MP caused inhibition of coelomocyte viability. Male reproductive organs were adversely affected. Negligible effects on female reproductive organs were observed.	(Kwak & An, 2021)
3.	*Lumbricusterrestris*; Polyethylene	Earthworms were exposed polyethylene at a concentration of 0 %, 7 % and 28 % in feeding litter, w/w for 40 days.	Microplastic at 28 % concentration caused 62.5 % mortality and 17.6 % weight loss in earthworms. Reproduction in earthworms was not affected by any treatment.	(Ju, Yang, Osman, & Geissen, 2023)
4.	*Eisenia fetida*; Polypropylene carbonate, polylactic acid, and polyethylene	Earthworms were exposed a gradient concentration of microplastics 0, 0.125, 1.25, 12.5, 125, 250 and 500 g/kg of artificial soil for 56 days.	Number of cocoons during reproduction was significantly reduced at 53 g/kg. 15-20 % death rate was observed from various concentration of MP. 27 % in the body weight loss was observed at MP concentration 500 g/kg of artificial soil.	(Ding et al., 2021)
5.	*Metaphireguillelmi*; High-density polyethylene and polypropylene	For 28 days, earthworms were let to live in soil that had been supplemented with 0.25 percent (w/w) high-density polyethylene (25 µm) or polypropylene (13 µm) microplastics.	Exposure to microplastics did not cause the specimen's gut microbiota to become dysbiotic. The bacterial community was changed and the diversity of bacteria was greatly decreased by microplastics.	(Cheng et al., 2021)
6.	*Eisenia fetida*; Polyethylene and polypropylene	Earthworms were exposed to 0.25 % (w/w) of polyethylene (28–145, 133–415 and 400–1464	Microplastic exposure altered SOD, CAT, and GSH activities. Microplastic exposure significantly disturbed several	(Li et al., 2021)

		µm) and polypropylene (8–125, 71–383 and 761–1660 µm) in an agricultural soil for 28 days.	pathways closely related to neurodegeneration, oxidative stress, and inflammatory responses.	
7.	*Eisenia fetida*; Polystyrene	Earthworms were exposed to a soil amended with polystyrene MPs concentrations 10 mg/kg and 100 mg/kg for 21 days.	Metagenomics sequencing and toxicity tests revealed MP caused toxicity and influenced the abundance of microbial community in specimen. 100 mg/kg of 10 µm MP significantly changed the profile of antibiotic resistance genes in earthworms.	(Xu & Yu, 2021)
8.	*Eisenia fetida*; Polystyrene	Earthworms were exposed to pure and commercial polystyrene microplastics (65-125 µm) (0-0.5 % w/w) in artificial soil for 28 days.	No toxicity effect on mortality was observed. Microplastics at 0.5 % concentration reduced 50 % juvenile production. Genotoxicity in terms of DNA damage was observed.	(Sobhani et al., 2021)
9.	*Eisenia andrei*; Polyethylene	Earthworms were exposed to polyethylene microplastic (<100 µm) at a concentration of 100 µg per kg of agricultural soil for 7 and 14 days.	Oxidative stress was observed in earthworms exposed to MP.	(Boughattas et al., 2021)
10.	*Eisenia andrei*; Polystyrene	Earthworms were exposed to microplastic at a concentration of 100 3g per kg of agricultural soil for 28 days.	No mortality could be observed after 28 days. No changes in avoidance behavior were observed. No significant changes of reproduction observed.	(Lackmann et al., 2022)

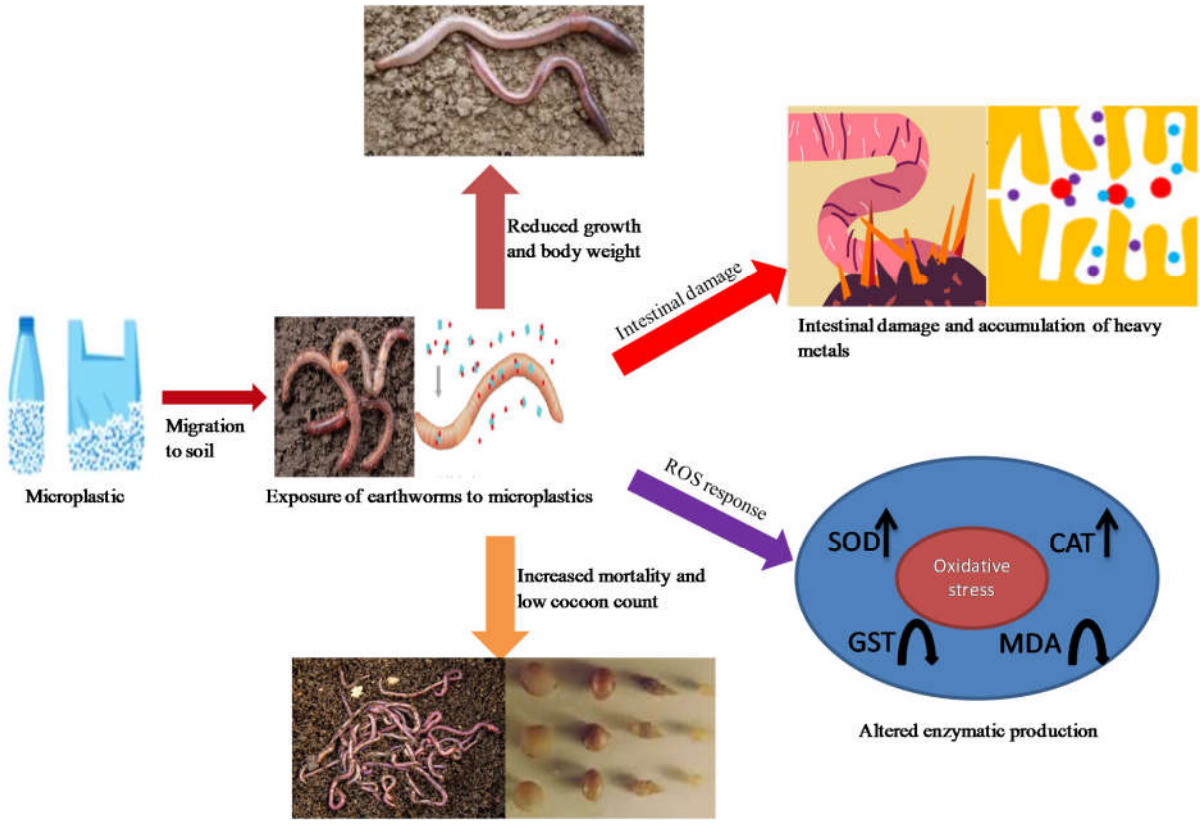

Figure 2: Exposure of earthworm to microplastics and their different harmful effects on growth, metabolism and reproduction.

Reproductive health

Growth and reproductive deficits are the outcome of MPs' toxicological effects (Figure 2). Studies have indicated that microplastics (MPs) have a deleterious impact on the growth and reproductive capabilities of earthworms **(Table 1)**. These consequences show up as decreased body weight, less cocoon formation, and changed progeny development. According to Tourinho et al. (2021), MPs fibers increased the toxicity of silver nanoparticles on *E. andrei* reproduction. The number of juvenile earthworms dropped to 35 when they were exposed to soil that included MPs fibers and silver nanoparticles (Tourinho et al., 2021). Ding et al. (2021) looked at the effects of polyethylene and biodegradable MPs on earthworms in a different study. Remarkably, the researchers discovered that the effects of polyethylene on *Eisenia fetida*'s reproductive system were comparable to those of biodegradable plastics like polylactic acid (PLA) and polypropylene carbonate (PPC). As MP concentrations increased, a drop in cocoon count was noted by the 28th day of harvest. The quantity of cocoons and juvenile earthworms showed a notable decrease (EC10) at doses of 53.0 g kg^{-1} and 97.0 gm kg^{-1}, respectively (Ding et al., 2021). Similarly, Sobhani et al. (2021) found that earthworm reproduction in both the F0 (parental) and F1 (first filial) generations was significantly reduced by more than 70% as a result of exposure to polyethylene MPs. Therefore, without the necessity for in-depth physiological research, evaluating reproductive health can act as a preliminary indicator to identify the hazardous effects of MPs on earthworms (Sobhani, Panneerselvan, Fang, Naidu, & Megharaj, 2021). In addition to changes in the way people reproduce. There are several more effects that MPs have been observed to have on organisms. For example, MP exposure may cause the synthesis of stress-related enzymes, which may indicate physiological stress reactions (Zou et al., 2023). Moreover, organisms may display avoidance behaviours in an effort to reduce their interaction with environments contaminated by microplastics. These findings underscore the necessity for thorough studies into the ecological effects of MPs and show the diverse effects of MPs that go beyond reproductive effects.

Other physiological effects

Microplastics have the capacity to alter the behavior of earthworms, leading to modifications in their burrowing activity and movement patterns (Jewett, Arnott, Connolly, Vasudevan, & Kevei, 2022). Exposure to MPs has been shown to result in reduced burrowing depth, diminished soil mixing, and changes in feeding behavior among earthworms **(Table 1)**. Moreover, MPs exposure can induce significant physiological and biochemical alterations in these organisms (Cong et al., 2022). Studies have reported elevated levels of oxidative stress, disruptions in antioxidant defence systems, and modifications in enzyme activities in earthworms subjected to MPs **(Figure 2)**. Li et al. (2021) looked into how polyethylene MPs affected the activities of catalase, glutathione peroxidase, and superoxide dismutase—three important antioxidant enzymes. The impact of polyethylene MP exposure on the activity of these enzymes in earthworms was investigated by the researchers (Li et al., 2021). Zhang and colleagues (2022) investigated the combination toxicity of zinc oxide and polyethylene nanoparticles on earthworms. An increase in the levels of catalase and glutathione synthetase altered antioxidant response in the presence of both polyethylene and zinc oxide nanoparticles. This indicates that the combined exposure to these particles can have a synergistic effect on the oxidative stress response in earthworms (Shuwu Zhang, Ren, Pei, Sun, & Wang, 2022). Chen et al. (2020) detected an augmentation in the activity of catalase and acetylcholinesterase in *E. fetida* when exposed to a concentration of 1 gm/kg of LDPE. This observation implies that the presence of low-density polyethylene can induce changes in the enzymatic activities related to antioxidant defence and neurochemical processes in *E. fetida* (Y. Chen, Liu, Leng, & Wang, 2020). Earthworms have a crucial role in preserving soil fertility and structure. However, the presence of MPs contamination in soil can have detrimental effects on earthworm-mediated processes, including nutrient cycling, soil aeration, and decomposition of organic matter (Liang, Lehmann, Yang, Leifheit, & Rillig, 2021). These processes are essential for maintaining a healthy and productive soil ecosystem. Thus, MPs' effects on earthworms may have a significant impact on the health of the soil and ecosystem function. As a result, these disruptions can set in motion a series of consequences that have implications for the overall strength of soil and the functioning of ecosystems. It is important to highlight that the toxicological effects of MPs on earthworms exhibit variability due to the interplay of multiple factors (Sun et al., 2021). These factors include the characteristics of the MPs, such as their type and size, as well as the specific species of earthworms involved. The concentration and duration of exposure to MPs are crucial determinants in shaping the extent of their effects on earthworms and, consequently, the resulting impact on soil health (de Souza Machado et al., 2018). It should be noted that the presence of other pollutants or environmental stressors can interact with MPs, potentially exacerbating their detrimental effects (Tourinho et al., 2021). These interactions between MPs and other contaminants or stressors can lead to synergistic or additive effects, amplifying the overall impact on organisms and ecosystems. Therefore, considering the potential interactions is essential for a comprehensive understanding of the ecological implications of MPs pollution. Zhang et al. (2022) found that the presence of MPs in soil led to higher bioaccumulation of zinc in *E. fetida* (Shuwu Zhang et al., 2022). This observation suggests that MPs can influence the uptake and accumulation of zinc by earthworms, potentially leading to increased levels of this metal within their tissues. In a study, Fu et al. (2023) observed that toxicity of polyethylene was enhanced in the presence of imidacloprid. This enhanced toxicity was indicated by alterations in the ferroptosis pathway, a form of programmed cell death, and an increase in the iron content within the tissues of *E. fetida* (Fu et al., 2023). Considering the toxic effects of MPs on earthworms, it is crucial to implement measures to minimize their presence in agricultural soil. Therefore, it is imperative to adopt strategies that reduce the starter and gathering of MPs in agricultural systems, safeguarding the beneficial role of earthworms and supporting sustainable agricultural practices.

REMOVAL TECHNIQUES OF MICROPLASTICS FROM SOIL

Removing MPs from soil can be a challenging task due to their small size and widespread distribution. However, there are several techniques that can be employed to mitigate and remove MPs from soil (Nabi, Bacha, & Zhang, 2022).

Physical

Physical separation involves the use of sieves or filters to isolated MPs from the soil sample. This technique is effective for larger MPs but may not be suitable for smaller particles. Soil washing is a technique where contaminated soil is mixed with water or other solvents to extract MPs (Kononov, Hishida, Suzuki, & Harada, 2022). This process relies on the difference in density between the soil particles and MPs. Centrifugation can be used to separate the MPs from the soil-water mixture. Electrostatic separation utilizes the principle of electrostatic charge to attract and separate MPs from soil. By applying an electric field, the MPs can be charged and subsequently separated from the soil (Enders, Tagg, & Labrenz, 2020).

Filtration is one of the several physical approaches that are used to mitigate MPs contamination; it is a notable approach. Screening, disk filtration, sand filtration, and membrane filtration (which includes micro - filtration, ultrafiltration, nano - filtration, dynamic membrane, and reverse osmosis) are among the various techniques that make up filtration (Cevallos-Mendoza, Amorim, Rodríguez-Díaz, & Montenegro, 2022). Both conventional wastewater treatment plants (WWTP) and drinking water treatment plants (DWTP) use screening. By combining the processes of sedimentation and filtering, the screening method effectively removes bigger plastic particles. The screening approach may remove MPs at a rate of about 40% to 80%, according to extensive research (Sadia et al., 2022). Meanwhile, disk filtration emerges as another widely used technique in WWTP settings. In their study, Simon et al. (2019) demonstrated the high efficiency of the diskfilter in removing MPs smaller than 10 μm, with a remarkable removal rate of up to 89.7%. Additionally, it's worth noting that a sandfilter is a versatile method employed in both conventional WWTP and DWTP for MPs removal (Simon, Vianello, & Vollertsen, 2019). According to the findings of Wolff et al. (2021), rapid sandfiltration exhibited impressive MPs removal rates, achieving approximately 99.2% ± 0.29% and 99.4% ± 0.15% (Wolff et al., 2021). As for membrane filtration, it demonstrated excellent efficiency in removing MPs, especially those larger than 10 μm, with most cases showing removal rates of over 90%. However, it is essential to acknowledge that while membrane filtration effectively removes MPs, it also presents a potential challenge. The deposition of MPs on the membrane surface can accelerate membrane contamination, leading to the contamination of other organic substances present in the membrane (Wan et al., 2022). To address this issue and prevent excessive membrane contamination, a pretreatment process becomes necessary when employing a membrane filtration method. This pretreatment process serves to safeguard the membrane from contamination by organic matter and MPs, ensuring its continued effectiveness in removing pollutants (Jianguo Zhang et al., 2023).

Chemical

Chemical degradation involves the use of chemical agents or enzymes to break down MPs into smaller, less harmful substances. This method can be effective for certain types of MPs but may not be suitable for all polymers (Zeenat, Elahi, Bukhari, Shamim, & Rehman, 2021). The utilization of chemical methods for MPs removal has been subject to extensive research, with coagulation/precipitation being a prominently employed approach in water treatment. However, the effectiveness of this method can vary significantly depending on numerous factors, including the specific form and amount of coagulant used, as well as the duration of coagulation retention (Azizi, Pirsaheb, Jaafarzadeh, & Nabizadeh Nodehi, 2023).

Numerous investigations have been conducted to identify the most suitable coagulant type and ideal conditions for efficient MPs elimination

(Koul et al., 2022; Kurniawan et al., 2020; Prokopova et al., 2021). Despite these efforts, there remains a need for further and more in-depth studies to establish clearer and more comprehensive guidelines for effective MPs removal using coagulation/precipitation methods in the future (Negrete Velasco, Ramseier Gentile, Zimmermann, & Stoll, 2022). Such studies would be valuable for enhancing our understanding of the mechanisms involved and for developing more efficient and targeted approaches for combating MPs contamination in water treatment processes. Lapointe et al. (2020) conducted a comparative analysis of the exclusion rates of different types of PE, weathered PE, and pristine PE MPs using a Jar test. They employed Al -based coagulants and polyacrylamide (PAA) as part of the treatment process. They found that 2.73 mg of aluminum per liter (Al/L) and 0.3 mg of poly acrylamide per liter (PAM/L) coagulants to water containing 500 MPs per liter (MPs/L), the optimal removal rates were quite similar. The removal efficiency for various microsphere sizes was as follows: 82% for PE microspheres of 140 µm, approximately 80% for PS (polystyrene) microspheres of 140 µm, about 88% for PE microspheres of 15 µm, and an impressive 99% for PEST (polyester) fibers. Moreover, the combination of PAM with aluminum-based and iron-based coagulants could achieve an efficient removal of microplastics, with removal rates reaching up to 99%. The effectiveness of the removal depended on factors such as the size and number of MPs, as well as the specific conditions of the water being treated. Additionally, the study also highlighted the efficacy of electrocoagulation as an effective method for removing microplastics from water (Lapointe, Farner, Hernandez, & Tufenkji, 2020). These findings provide valuable insights into the potential application of coagulation and electrocoagulation techniques for efficient microplastics removal, and they underscore the importance of considering different factors when designing effective strategies to combat microplastic pollution in water bodies.

Biological Removal Technology

Bioremediation relies on the activity of microorganisms to degrade or assimilate MPs in soil. Certain bacteria and fungi have the ability to break down or metabolize MPs, leading to their removal from the environment (Vaksmaa et al., 2023). Phytoremediation involves using plants to extract or degrade contaminants, including MPs, from soil. Some plant species have the ability to take up MPs through their roots and store them in their tissues, thereby reducing the MPs concentration in the soil (Yan et al., 2020).

Lagoons, septic tanks, aerobic and anaerobic digestion, activated sludge treatment, and other biological treatments have been found to have superior removal effectiveness when it comes to MPs (Park & Park, 2021; X. Zhang, Chen, & Li, 2020). Bacteria are known to be able to attach themselves to MPs smaller than 0.5 mm in activated sludge systems. However, although the activated sludge system efficiently removes microplastics from water, it is still difficult for it to break down plastics because of the short residence duration (7–14 hours) in WWTPs (Kiran, Kopperi, & Venkata Mohan, 2022).

A study on virgin MPs by Liu et al. (2019) found no statistically significant impact of these particles on the activity of important microbial groups, including phosphorus-accumulating organisms, nitrite oxidizing bacteria, and ammonia oxidizing bacteria (G. Liu et al., 2019). On the other hand, Cunha et al. (2020) used 10.00 mg/L of fresh *Cyanothece* sp. in a different study and found an impressive clearance rate of up to 47% for microplastics (Cunha et al., 2020). Canniff and Hoang (2018) investigated Daphnia magna's growth rate in response to PE beads. They discovered that longer exposure times and greater particle concentrations led to an increase in the ingestion rate of PE beads. They also noticed that *Raphidocelis subcapitata* that had been exposed to PE beads had grown more than those that had not. Notwithstanding these results, it was discovered that the overall effectiveness of eliminating MPs with biological techniques was typically modest (Canniff & Hoang, 2018). Furthermore, secondary contamination may result from MPs in sludge or sedimentation. Therefore, it's critical to avoid overstating how MPs affect bioreactor system performance. This leads one to the conclusion that biological techniques are not particularly promising for achieving high MPs elimination efficiency (Okoye et al., 2022).

It is crucial to acknowledge that the efficacy of these methodologies can diverge contingent on the nature and dimensions of MPs, alongside the soil's composition. In numerous instances, a synergistic approach encompassing various techniques might be necessary to attain the most favourable outcomes. Furthermore, fostering improved waste management practices and curbing plastic pollution at its source are imperative for establishing enduring solutions.

FUTURE PERSPECTIVES

The extensive existence of MPs in terrestrial ecosystems, including soils, has elevated significant alarms about their toxicological effects on earthworms and the overall health of soil ecosystems. This review article provides valuable insights into the impact of MPs on earthworms and highlights the urgent need to address this environmental challenge. It also explores the emerging removal technologies for mitigating MPs pollution in soils, aiming to preserve the health and functionality of earthworms and soil ecosystems. The toxicologic effects of MPs on earthworms have been well-documented, encompassing both physical and chemical interactions. Earthworms can ingest MPs, leading to mechanical damage and hindrance of vital physiological processes. The accumulation of MPs in earthworm tissues can disrupt digestion, impair coelomic fluid movement, and affect reproductive and developmental processes. Furthermore, MPs can act as carriers for various organic pollutants, potentially leading to internal exposure and toxicity in earthworms. These toxicological effects have far-reaching implications for the overall health and functioning of soil ecosystems, given the critical roles that earthworms play as ecosystem engineers.

To address the challenge of MPs contamination, several removal technologies have been developed. Physical removal methods, such as filtration, centrifugation, and electrostatic separation, aim to physically separate MPs from soil matrices. Chemical remediation methods, including biodegradation and chemical degradation, utilize biological or chemical agents to break down MPs into less harmful forms. Phytoremediation, involving the use of plants, and microbial remediation, utilizing specific microorganisms offer a promising approache for removing MPs from soils. Integrated approaches that combine multiple removal technologies are also being explored to enhance the efficiency and effectiveness of MPs remediation. However, it is important to acknowledge that the removal of MPs from soil is a complex and challenging task. The diverse nature of MPs, their varying sizes, shapes, and compositions, as well as their interactions with soil particles, make their complete removal a formidable challenge. Additionally, the long-term effects of these removal technologies on soil ecosystems and the potential unintended consequences need further investigation.

Moving forward, there is a need for improved risk assessment methods to better understand the toxicity of MPs to earthworms and the broader soil ecosystem. Standardized testing protocols should be developed to ensure consistent and reliable data collection and interpretation. Long-term studies are essential to assess the chronic effects of MPs exposure on earthworm populations, soil health, and ecosystem functioning. Furthermore, regulatory frameworks and policies must be developed to mitigate the issue of MPs into the environment and promote the adoption of sustainable practices.

Education and public awareness play a vital role in addressing the issue of MPs pollution. Efforts should be made to raise awareness about the environmental impacts of MPs and the importance of responsible plastic use and disposal. Public engagement and participation are crucial in driving behavioural changes and fostering a collective responsibility towards mitigating MPs pollution.

CONCLUSION

In conclusion, this review article provides valuable visions into the toxicological effects of MPs on earthworms and highlights the urgent need to address this global environmental challenge. The development of effective removal technologies is crucial for mitigating MPs contamination in soils, ultimately preserving the health and functionality of earthworms and soil ecosystems. Future research and collaborative efforts are necessary to further our understanding of MPs toxicity and develop sustainable solutions to combat this pervasive environmental problem. By safeguarding earthworm populations and soil ecosystems, we can ensure the long-term health and sustainability of our planet.

Further research is needed to gain a more comprehensive understanding of the mechanisms and long-term consequences of MPs exposure on earthworms and soil ecosystems. Nonetheless, the available evidence suggests that MPs can have detrimental effects on earthworms, underscoring the need to mitigate MPs pollution and protect soil health.

Acknowledgement
Authors acknowledge the infrastructural and monetary support provided from Department of Zoology, Maharshi Dayanand University, Rohtak-124001, Haryana, India. G.S. is grateful to Council of Scientific and Industrial Research (CSIR) for grant of junior research fellowship (JRF).

Credit author statement:
Author contributions: Garima Sheoran: Literature search, Data analysis, Software, Writing original draft. **Vineeta Shukla:** Conceptualization, Resources, Supervision, Visualization, Writing - review & editing.
Data availability: All data generated or analyzed during this study are included in this published article

Conflict of interest:
The authors declare that they have no conflict of interest with contents of this article.

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