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Review article

Microplastic-Earthworm Interactions: A Critical Review

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ABSTRACT

Microplastics generated from diverse categories of plastic wastes primarily accumulate in terrestrial ecosystems and subsequently find their way to aquatic ecosystems. As the use of plastic goods has been increasing globally during the last few decades, it is likely that the amount of microplastics too would increase significantly and get accumulated in the soil. An increased level of microplastics might have deleterious effects on soil properties and microbiota. Microplastics being small (< 5 mm), could be easily consumed by pedophagous soil fauna such as earthworms and get dispersed widely in soil and might even reach the groundwater table. It has been reported that microplastics such as polyvinyl chloride, polypropylene etc., can bind to toxic compounds, including pesticides and transfer these into the gut of earthworms, adversely impacting their growth, ecological functions, and reproduction. It is apprehended that earthworms and other soil fauna could accelerate the degradation of microplastics into nano forms which could enhance environmental risk not only for these animals but also for other beneficial soil biotas.

Key words: Soil, biota, secondary pollutants, bioindicator, xenobiotics, pollution, adsorbent

INTRODUCTION

The worldwide plastic production amounted to 359 million tons in 2018, and projections suggest that it could increase to 33 billion tons by 2050 (Anonymous 2019). Out of all plastic wastes generated between 1950 and 2015, about 79%, i.e., 6300 megatons, was discarded directly into the environment or the landfills, predominantly in soil (Geyer et al. 2017, Zhu et al. 2019, Lin et al. 2020). The accumulated plastic wastes break down into smaller fragments and particles due to physical, chemical, and biological actions in the environment. This breakdown results in the formation of plastics <5mm in size, called microplastics (MPs) (Thompson et al. 2004). The atmospheric deposition, land application of sludge, agricultural plastic film, etc., result in the generation of MPs (Zhu et al. 2019). Municipal sludge contains synthetic fibres used in personal care or household products as sediments. Its application in the land has been identified as the major input of MPs into the soil (Horton et al. 2017). According to reports, the occurrence of MPs in organic fertilizers produced through biowaste fermentation and composting has been observed. The presence of MPs, with levels reaching up to 895 particles per kg, is believed to serve as a pathway for their introduction into the soil (Weithmann et al. 2018). Studying the mechanism of the degradation of MPs in soil and their probable impact on the biota has been one of the biggest challenges (Alimi et al. 2018, Mishra et al. 2022b). The soil ecosystem is susceptible to MP contamination since it could adversely impact beneficial soil organisms like earthworms and microorganisms (Samal et al. 2020, Mishra et al. 2022a).

EARTHWORMS AND THEIR ECOLOGICAL FUNCTIONS

Soil fauna not only regulates soil diversity but also maintains the ecological balance. The earthworm is considered the dominant soil fauna. It has been reported to be a sensitive bio-indicator (Fusaro et al. 2018). The activity zone of earthworms in soil is known as the drilosphere (Hickman and Reid 2008). It includes the burrows, worm casts, biological systems, physicochemical interactions, and associated organisms (Hickman and Reid 2008). The soil's physical and chemical properties, nutrients, and rainfall patterns influence earthworm diversity (Acharya and Mishra 2020). Their feeding and burrowing behaviour facilitate the breakdown of soil organic matter and turnover of soil nutrients. This aids in the structural development of soil aggregates (Adhikari and Hartemink 2016). Three main ecological types of earthworms have been recognized depending on their soil burrowing movement. These are (a) anecic, (b) endogeic, and (c) epigeic (Butt and Lowe 2010). The deep-burrowing species that can form continuous, permanent, vertically running burrows from the soil surface to the subsoil are anecic earthworms. The endogeic earthworms build burrows and live under the soil surface, which they then refill with the cast (Fig. 1). Most epigeic earthworms do not form burrows and are generally litter feeders (Chatelain and Mathieu 2017).

Earthworms are recognized as "keystone species" due to their significant contribution to the soil formation process, underscoring their crucial role in ecosystem functioning. They have also been described as 'ecosystem engineers' (Wright et al. 2013). Earthworms form pores in the soil while they move through it. It has been found that soil aggregation of <0.4mm in the fraction was predominant in treatment without an earthworm population, compared to earthworm-treated soil. The porous soil has increased surface area, influencing physical, chemical, and biological properties (Zaffar and Lu 2015). The ecological category and preferences determine the movement of earthworms in soil (Gergs et al. 2022). *Aporrectodea caliginosa*, an endogeic earthworm, is common in arable fields in Europe (Le Couteulx et al. 2015, Bart et al. 2018, Jouni et al. 2018) which are predominantly active within the upper soil layer, creating branched horizontal burrows. It has been demonstrated that the presence of earthworms significantly helps plant growth (Mayilswami and Reid 2010) by facilitating nutrient availability in the soil. A meta-analysis revealed that the earthworms increase crop yield by 25% and above-ground biomass by 23% (van Groenigen et al. 2014). The earthworm *Millsonia anomala* caused an increase in leaf weight, cob biomass, and the number of cobs of maize by 40,

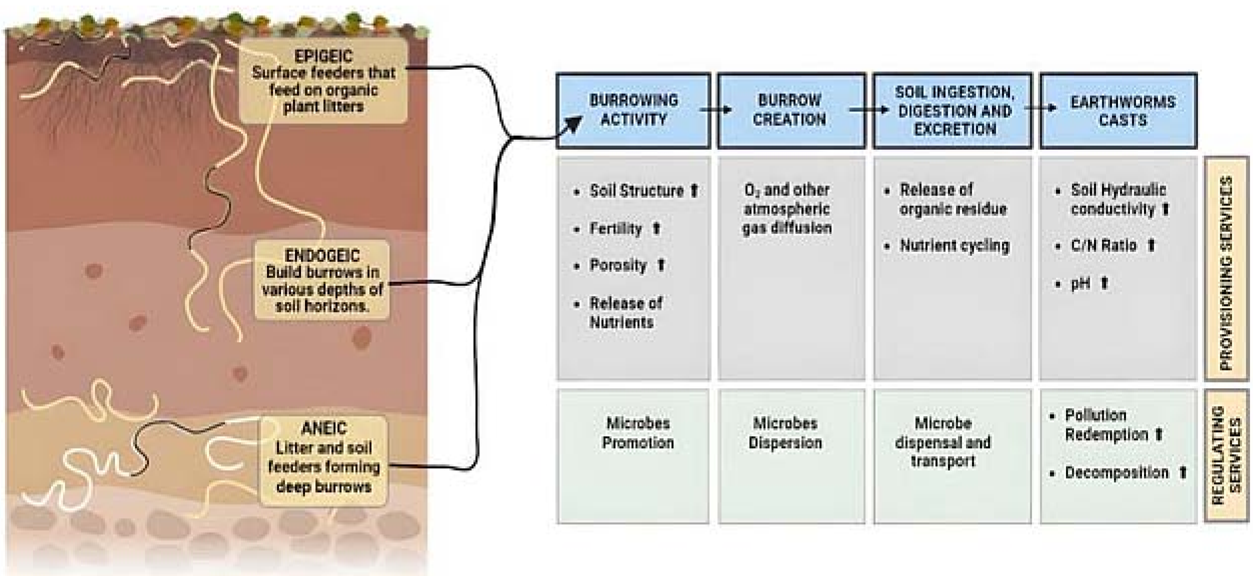

Figure 1. Functional role of earthworms in soil

152, and 130%, respectively. Earthworms influence the distribution of soil organic materials, increasing soil penetrability and ion transport in soils under certain environmental conditions. Earthworm tissues and cast material are enriched in certain nutrients concerning the soil matrix, but the rate of cycling increases by ingesting soil organic material. The earthworm has a remarkable ability to bio-accumulate the residues of toxic organic substances, including pesticides, herbicides, antibiotics, and heavy metals into their tissue (Byambas et al. 2019, Mishra et al 2020, Samal et al. 2020).

MICROPLASTICS

The production of plastics has recently touched around 280 million tons globally (Yu et al. 2022). Plastic wastes are now considered to be the major environmental pollutants. An enormous number of plastics accumulate in the marine and terrestrial ecosystems as waste materials (Rillig 2012, Mishra et al. 2022a). Large plastic pieces accumulate in soil are mainly due to anthropogenic influence (Rillig et al. 2017). Only 20% of plastic wastes is recycled (Letcher 2020). Plastic debris with a size of less than 5mm is known as microplastics (MPs) (Wright et al. 2013, Alimi et al. 2018, Rochman and Hoellein 2020). Various environmental weathering processes, such as mechanical breakdown, microbiological decomposition, and photodegradation result in the formation of MPs of variable shapes and sizes (Lenaker et al. 2019, Xu et al. 2021). These are found to contaminate a wide range of aquatic environments (Lambert and Wagner 2018). MPs generated from diverse groups of plastic polymers accumulate in soil. The probable adverse ecological impact of MPs has encouraged scientists to undertake elaborate studies on their effects on biota (Boots et al. 2019). Industrial manufacturing (Lei et al. 2017), solid waste landfill (Andrady 2017), agriculture plastic mulching (Gao et al. 2019), sewage irrigation (Li et al. 2018), and sludge fertilizer (Mahon et al. 2017), soil amendment application (Weithmann et al. 2018), fertilizer coatings (Bian et al. 2022), and littering (Yang et al. 2021), are the major causes for the origin of MPs. Strong hydrophobicity, small particle size, large specific surface area, stable chemical properties, and adsorption of other environmental pollutants such as antibiotics, heavy metals, and toxic chemical residues by MPs pose huge environmental risks (Alimi et al. 2018, Karbalaei et al. 2018, Kumar et al. 2020, Rillig and Lehmann 2020, MorenoJiménez et al. 2022, Yu et al. 2022).

Types

MPs are generally classified as per sources into two categories, primary and secondary (Lots et al. 2017). Manufactured plastic objects that satisfy specific uses, such as clothing fibres and personal care products, are primary MPs (Andrady 2011). These are manufactured as microbeads and microfilaments for commercial use, particularly in cosmetics and synthetic fabrics (Cole et al. 2013). The secondary MPs are the tiny fragments of more oversized plastic items generated from natural weathering in the environment (Lehtiniemi et al. 2018) (Fig.2). Secondary MP sources are the large plastic pieces through photodegradation and mechanical abrasion in natural environments (Siegfried et al. 2017).

Toxicity

Various additives may be present with MPs that are generally not chemically bound to plastic polymers. These may be prone to leaching into the soil matrix (Hahladakis et al. 2018, Ge et al. 2021). Plastics in soil degrade due to physical, chemical, and microbial action. This results in releasing harmful substances which include phthalates, bisphenol A, polybrominated diphenyl ethers, and heavy metals (Hahladakis et al. 2018). These substances adversely impact soil properties and the soil ecosystem. Studies have indicated that soil MP toxicity is related to its characteristics and extractable additives (Kim et al. 2020). The environmental risk due to MPs on biota significantly increases in the presence of pesticide residues in agricultural soil (Mishra et al. 2022b). The characteristics of MPs, such as their small particle size, large surface area, and hydrophobic surface, contribute to their ability to accumulate environmental contaminants from the surrounding ecosystem. Consequently, concentration of the contaminants in MPs can be hundreds or even thousands of times higher compared to the surrounding environment (Zhao et al. 2021). In the co-exposure of MPs and environmental pollutants, MPs may transfer contaminants and increase their accumulation in organisms (Zhou et al. 2021). Stronger phytotoxicity, reduction in plant biomass, photosynthetic inhibition, reduced root activities, and oxidative damage might result from the combined exposure of MPs and heavy metals (Chen et al. 2020, Dong et al. 2021).

Transportation

The transformation and transportation of MPs depend upon the surrounding conditions and these accumulate in plants and organisms, which causes a direct impact on individual species. It also impacts the trophic chain composition and the soil ecosystem (Mendes 2021). MPs get accumulated in soil and transported by the soil fauna, such as earthworms, mites, and bouncing bugs, through their feeding and burrowing behaviours (Maaß et al. 2017) (Fig.2). The dispersion and redistribution of MPs also occur by mites, bullet tails, gophers, and moles. They can scrape or chew MPs (Maaß et al. 2017, Zhu et al. 2018). The migration of MPs can also be influenced by the growth of plant roots. For instance, the presence of corn roots leads to the creation of additional soil pores and gaps, potentially affecting the movement of MPs. These soil pores and gaps are conducive to the upward movement of MPs in soil up to 7–12 cm (Li et al. 2021a).

Adsorbents

MPs act as potent adsorbents of various pollutants (Fig. 2), such as heavy metals and agrochemicals. MPs function as adsorbers of plastic additives, including plasticizers and flame retardants, as well as other environmental pollutants, such as organic contaminants and heavy metals (Wang et al. 2020). Recent studies have indicated that MPs such as polyvinyl chloride and polypropylene could absorb pesticides monocrotophos, glyphosate, butachlor and pretilachlor forming hydrogen bonds (Fig. 3) and facilitate in the intake of these toxic compounds into the earthworm gut (Mishra et al. 2022a). The chemical additives to MPs can easily leach into the soil with consequent adverse effects on plant growth. The rate of adverse effects is directly proportional to the rate of adsorption capacity of the MPs. This depends on the shape, polymer structure, degradation, additives, concentration, and location of the MPs (Lozano and Rillig 2020, Zhou et al. 2021, Okeke et al. 2022).

Interaction with soil biota

Research on MP in soil has so far focused on earthworms and nematodes. However, other invertebrate taxa, such as enchytraeids, collembolans, terrestrial snails, isopods, and oribatid mites have also been investigated (Selonen et al. 2020, Song et al. 2019) to some extent. Most of the focused research areas include growth (Xiang et al. 2019, Boots et al. 2019), survival, reproductive fitness and success (Kim et al. 2020, Lahive et al. 2019, Qu et al. 2019), disruption of ingestion behaviour (Song et al. 2019), response to oxidative stress (Chen et al. 2020, Zhou et al. 2021), locomotion (Kim and An 2019, Qu and Wang 2020), and change in expression in the gene (Qu and Wang 2020, Yang et al. 2021). Terrestrial organisms may ingest MPs (Fig 2). For example, ciliates, amoeba, flagellates, springtails, and earthworms ingest MPs resulting in decreased survival and growth rates, intestinal damage and immune disorders, oxidative stress, neurotoxicity, damage to DNA and abnormally expressed genes (Sarker et al. 2020, Wang et al. 2020, 2022a) in these animals. These can even be transferred along the food chain (Huerta Lwanga et al. 2017). MPs accumulate in the guts and stomachs of soil organisms, damaging their immune system (Fig. 2). It also affects their feeding behaviour and development (Ding et al. 2019, Eltemsah and Bøhn 2019, Gao et al. 2019). MPs also damage earthworms' gut cells and DNA (Jiang et al. 2020). Research has also shown that MPs harm invertebrate sperms (Kwak and An 2021). In addition, the diversity and richness of the gut microbiome of soil animals may be changed due to microplastics, which may participate in the cycle of essential elements and soil organic matter decomposition (Zhu et al. 2018). The impacts of MPs on animals are intricately linked to factors such as the concentration, shape, size, type, and additives of the MPs to which they are exposed (Lambert et al. 2017, Wang et al. 2019, Chen et al. 2020, Li et al. 2021b).

INTERACTION BETWEEN EARTHWORMS AND MICROPLASTICS

Dispersal by earthworms

Earthworms, specifically anaecic and endogeic ones, can carry MPs deep into the soil. These get transported via casts and burrows. For example, polyethylene is

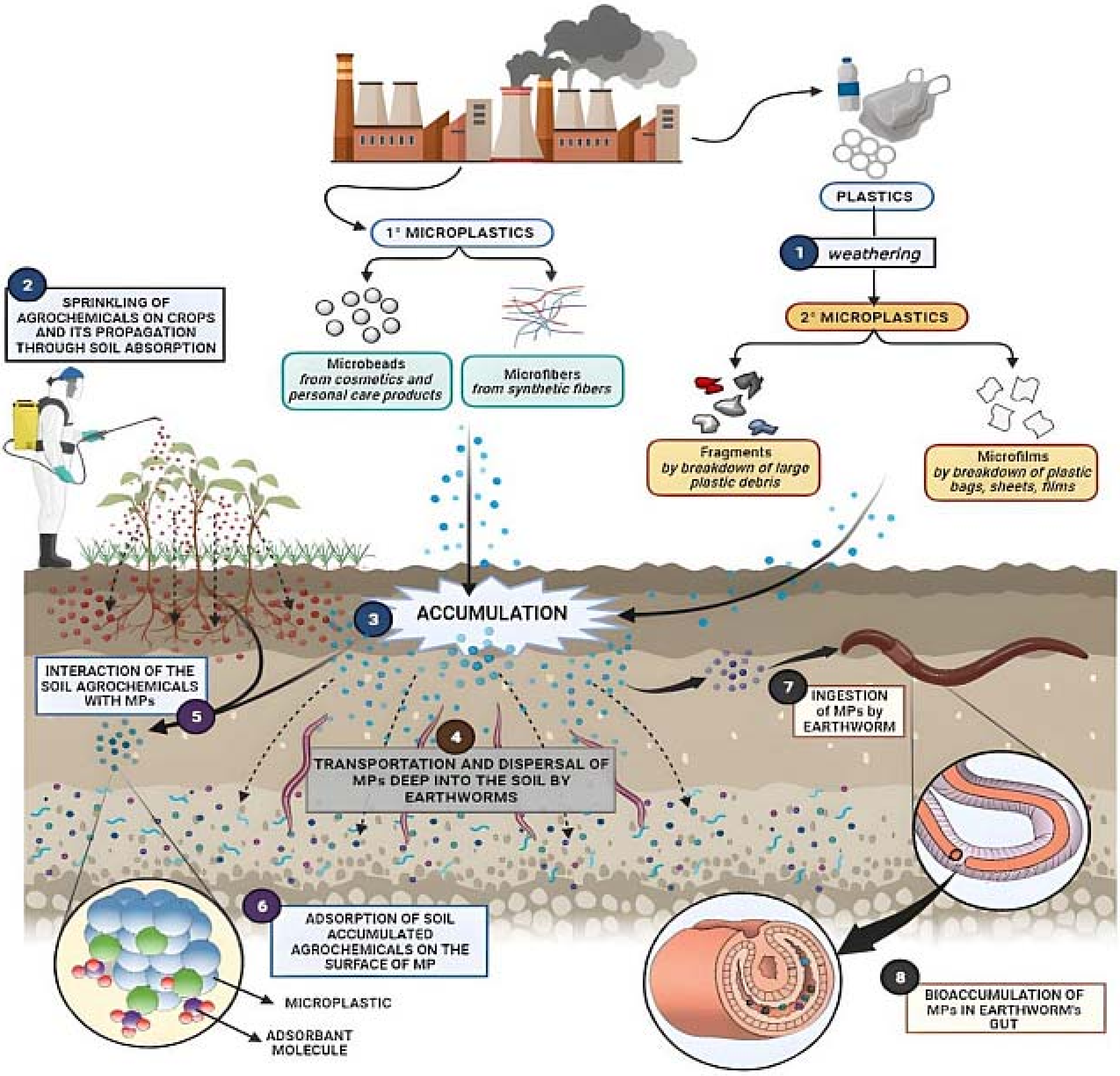

Figure 2. Genesis, transportation and impact of microplastics in the terrestrial ecosystem

transported to a depth of 10 cm in soil vertically, because of which soil biotas get exposed to MPs. MPs have been reported to reach the groundwater table (Rillig et al. 2017). The introduction of MPs in soil could have a wide-ranging impact on earthworms as (i) MPs might adversely influence soil microbial growth, and due to the reduced microbial population, the decomposition of organic material is generally much slower deeper in the soil. This indicates that the longer persistence of MPs in deep soil could impact the nutrient pool (Rillig et al. 2017); (ii) After passage through soil strata, MPs finally reach the groundwater table, which can have long-ranging detrimental effects (Rillig et al. 2017, Stock et al. 2021); and (iii) MPs, under further mechanical disintegration, may become nano-sized particles with different characteristics and environmental risks (Rillig et al. 2017).

Impact on earthworm health

MPs accumulate in the gut or stomach of earthworms and other soil fauna and have adverse effects on these animals (Bergami et al. 2016, Yu et al. 2020). Accumulation of microplastics could adversely affect the feeding behaviour, growth, and development of soil animals (Yu et al. 2020). Particles in smaller sizes

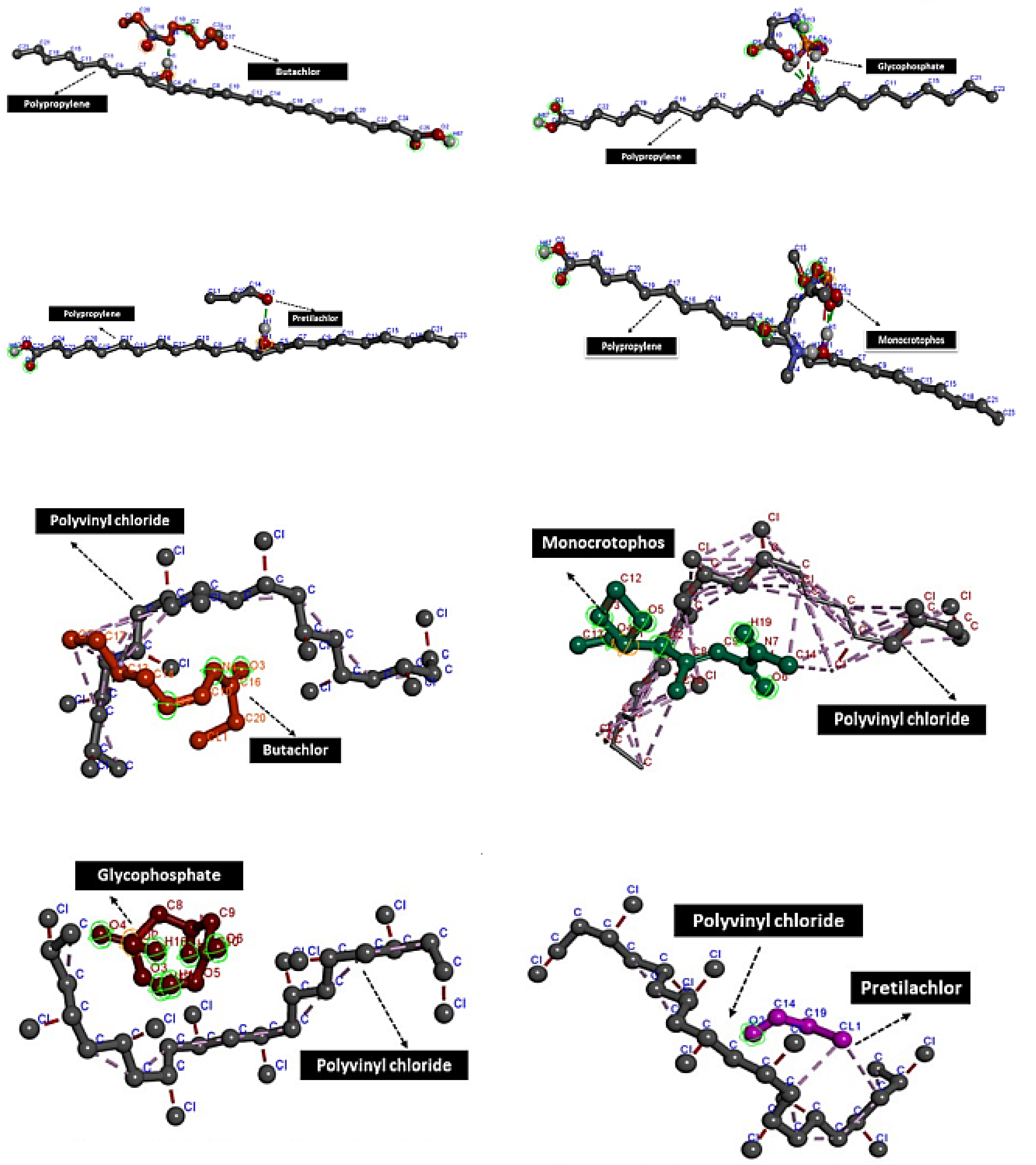

Figure 3. Molecular interaction of microplastics with pesticides

can penetrate the cell membranes, translocated in tissues, and then enter the trophic levels (Shen et al. 2019). Due to higher abundance, smaller micro and nano-plastics may be harmful to soil biota (Qi et al. 2020).

Effects on the burrows

The X-ray visualization of the endogeic earthworm burrowing activities in soil cores identified the burrow parameters. These were the key factors of water transfer. A low LDPE concentration didn't affect saturated water flow (Yu et al. 2020). *L.*

terrestris made more burrows when the soil surface was treated with 7% MPs (Huerta Lwanga et al. 2017).

Degradation by earthworms

The adult earthworms, *Eisenia fetida's* avoidance behaviour to MP contaminated soil was assessed. Fossil-based polyethylene terephthalate (PET) and bio-based polylactic acid (PLA) MPs were found to be preferred by earthworms. The selective preference was likely due to the odour of the polymer monomers. The analysis of earthworm cast by microscopy counting and liquid chromatography-tandem mass spectrometry indicated MP excretion. The elimination half-life was 9.3 hours for polyethylene terephthalate (PET) and 45 hours for polylactic acid (PLA). The more extended excretion period of PLA could be related to its potential to break down in the earthworms' digestive tract (Wang et al. 2022b).

IMPACT ON SOIL PROPERTIES AND FUNCTIONS

MPs get dispersed in the soil matrix after entering the soil environment under the effects of dry and wet cycles, soil management measures, and biological disturbances (O'Connor et al. 2019). As a result, soil physicochemical properties change, which might include levels of C, N, and P and pH (Jiang et al. 2020, Qi et al. 2020, Wang et al. 2022a). MPs not only release chemical additives but also adsorb various toxic substances. This aggravates soil pollution and affects soil properties (Hahladakis et al. 2018, Zhang Z. et al. 2022). Soil porosity and water holding capacity are increased by MPs, and reduce their bulk density and moisture permeability (de Souza Machado et al. 2019, 2018, Jiang et al. 2020). MPs also destroy their structural integrity (Wan et al. 2019, Jiang et al. 2020) and their structure (Zhao et al. 2021).

Soil enzymatic actions can be inhibited or stimulated due to MPs (Brendel et al. 2018, Qian et al. 2018, de Souza Machado et al. 2018, 2019, Fei et al. 2020, Yu et al. 2020, Ren et al. 2021). The presence of MPs in soil may affect microbial diversity and community structure (Lei et al. 2017, Awet et al. 2018, Hou et al. 2021). Activities of certain soil enzymes, FDAse and phenoloxidase got stimulated at a high concentration of polypropylene (28% w/w), while a low concentration (7% w/w) had no significant effect (Li et al. 2020). The type of polymer in MPs and exposure time influence their impact (Yu et al. 2022). Any change in soil physicochemical properties and nutrient cycle by MPs in agricultural ecosystems leads to an unpredictable impact on greenhouse gas emissions. It has been documented that MPs could affect soil CO_2, N_2O, and CH_4 emissions (Brusseau et al. 2020, Ren et al. 2020, Gao et al. 2021).

CONCLUSIONS

MPs generated from plastic waste materials pose a significant threat to the soil ecosystem. The impact of micro and nano plastics on terrestrial ecosystems needs an elaborate study to find out how the below-ground food web is influenced by their accumulation. Studies should also focus to elucidate the potential role of MPs as adsorbents of toxic environmental contaminants. MPs, in combination xenobiotics, could enter the food webs of below-ground and above-ground ecosystems with very serious consequences. Earthworms, which play a dominant role in the soil are likely to be impacted adversely due to MP contamination with a consequent reduction in their ecological functions. MPs, too, could interfere in the growth and reproduction of earthworms, population and diversity of soil microbes, decomposition of organics, and nutrient availability with consequent detrimental effects on soil health.

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