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Review article

The forgotten impacts of plastic contamination on terrestrial micro- and mesofauna: A call for research

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ABSTRACT

Microplastics (MP) and nanoplastics (NP) contamination of the terrestrial environment is a growing concern worldwide and is thought to impact soil biota, particularly the micro and mesofauna community, by various processes that may contribute to global change in terrestrial systems. Soils act as a long-term sink for MP, accumulating these contaminants and increasing their adverse impacts on soil ecosystems. Consequently, the whole terrestrial ecosystem is impacted by microplastic pollution, which also threatens human health by their potential transfer to the soil food web. In general, the ingestion of MP in different concentrations by soil micro and mesofauna can adversely affect their development and reproduction, impacting terrestrial ecosystems. MP in soil moves horizontally and vertically because of the movement of soil organisms and the disturbance caused by plants. However, the effects of MP on terrestrial micro-and mesofauna are largely overlooked. Here, we give the most recent information on the forgotten impacts of MP contamination of soil on microfauna and mesofauna communities (protists, tardigrades, soil rotifers, nematodes, collembola and mites). More than 50 studies focused on the impact of MP on these organisms between 1990 and 2022 have been reviewed. In general, plastic pollution does not directly affect the survival of organisms, except under co-contaminated plastics that can increase adverse effects (e.g. tire-tread particles on springtails). Besides, they can have adverse effects at oxidative stress and reduced reproduction (protists, nematodes, potworms, springtails or mites). It was observed that micro and mesofauna could act as passive plastic transporters, as shown for springtails or mites. Finally, this review discusses how soil micro- and mesofauna play a key role in facilitating the (bio-)degradation and movement of MP and NP through soil systems and, therefore, the potential transfer to soil depths. More research should be focused on plastic mixtures, community level and long-term experiments.

1. Introduction

Plastic pollution in developing nations is one of the most serious and worrying concerns, with extensive environmental and human health consequences that must be tackled as a priority. Plastic debris are a heterogeneous class of man-made polymers that may vary significantly in size, structures, chemical compositions, physical characteristics, and applications. In this sense, microplastics (MP) are anthropogenic

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particles that may be identified in tiny quantities in the environment; yet, even at these low concentrations, they can pose major difficulties for living biota, including humans (Ahmed et al., 2022). Microplastics, defined as plastic particles with a maximum size of 1 mm, while nanoplastics fall in the range of 1 nm to 1 μm, are also growing, globally dispersed micropollutants (Hartmann et al., 2019; Padervand et al., 2020; Dissanayake et al., 2022). Their existence has been confirmed in a variety of aquatic settings across the globe, including oceans and seas, lakes, rivers, and dams, as well as in isolated places, such as alpine environments or Antarctica, through atmospheric transport (Bergami et al., 2020; Büks and Kaupenjohann, 2020; Evangeliou et al., 2020; Huerta Lwanga et al., 2022; Dissanayake et al., 2022).

In recent years, the focus of concern over MP in the environment has steadily migrated from the aquatic to the terrestrial environments (Horton et al., 2017; de Souza Machado et al., 2018a; Rodríguez-Seijo and Pereira, 2020). As soil is one of the most valuable resources, responsible for a wide variety of crucially important ecosystem processes and services, essential to the survival of humans and other creatures. Due to the greater release of MP to terrestrial ecosystems, soils may be more at risk of contamination by MP than oceans (Horton et al., 2017; Baho et al., 2021). Soil is a vast sink for MP that comes from various sources reviewed in recent years, from agricultural uses to washing machine clothes, aerial deposition or car abrasion tyres (Chia et al., 2022; Periyasamy and Tehrani-Bagha, 2022; Sajjad et al., 2022). Although some of them have recently been identified, most of them have still been neglected: landfills and waste management areas (He et al., 2019), packaging materials and industrial uses, synthetic microfibers from clothes on wastewater for irrigation or sewage sludges for fertilization (Ng et al., 2018: Weithmann et al., 2018; FAO, 2021; Wang et al., 2022a,b), agricultural plastics degradation (e.g., greenhouse covers, mulching applications, water pipes, hydroponic cultures) (Bläsing and Amelung, 2018; Büks and Kaupenjohann, 2020; Rodríguez-Seijo and Pereira, 2020; Okeke et al., 2023), car tire degradation (Kole et al., 2017), atmospheric deposition (Zhang et al., 2020a), spray paintings (Xu et al., 2022), etc (Fig. 1). An increasing number of studies indicate that MP may induce environmental change in terrestrial systems, and this evidence is developing. Besides, during the COVID-19 pandemic, the widespread use of disposable masks, protective masks, covid tests or other single-use plastic items significantly impacted terrestrial and aquatic ecosystems. This represents a big issue in the content and distribution of microplastics and nanoplastics in the environment that also requires more studies, primarily due to the possibility of single-use plastics as disease carriers (Aragaw, 2020; Benson et al., 2021; Celis et al., 2021; Zhao and Zhang, 2023). Although some researchers have indicated that single-use plastics could be relatively biodegraded (Ali et al., 2023), several questions are unclear due to this significant input of plastics to the environment and their potential impact on soil organisms (i.e., Kwak and An, 2021; Knicker and Velasco-Molina, 2022). Therefore, MP in soils is an environmental concern due to its widespread distribution and potential risks to all ecological systems.

Microplastics can potentially change the properties of several important soil biogeochemical processes. This, in turn, may have diverse consequences on the activities and functions of soil microorganisms. Microplastics are distributed in the soil matrix after entering the soil environment due to biological disturbances, soil management practices, etc. In general, the presence and long-term accumulation of MP in soils have been observed to change soil properties (e.g., physical and chemical properties such as soil structure, nutrient cycle, physicochemical properties etc.) (de Souza Machado et al., 2018b; 2019). For example, Lately, Wang et al. (2020) have pointed out that MPs in soils could alter soil physical properties such as soil bulk density and water holding capacity (by altering the soil's porosity, which in turn impacts soil water dynamics) and soil structure (through accelerating soil water evaporation by creating channels for water movement). In addition, a study by Kim et al. (2021) showed that MP in the soil could change soil organic carbon (SOC) in the short term, thus leading to an overestimation of SOC estimation in the quantification process. All these processes ultimately affect the soil's physicochemical parameters, such as its C, N, and P content, water availability through soil porosity and changes in water holding capacity, soil pH, organic matter cycles, soil enzymatic activities, etc. (de Souza Machado et al., 2018b, 2019; Rodríguez-Seijo and Pereira, 2020; Qi et al., 2019, Zhang et al., 2020b, 2022a,b; Chia et al., 2021,2022a; Dissanayake et al., 2022; Wang et al., 2022a). However, some fundamental concerns about MP in the soil, such as their

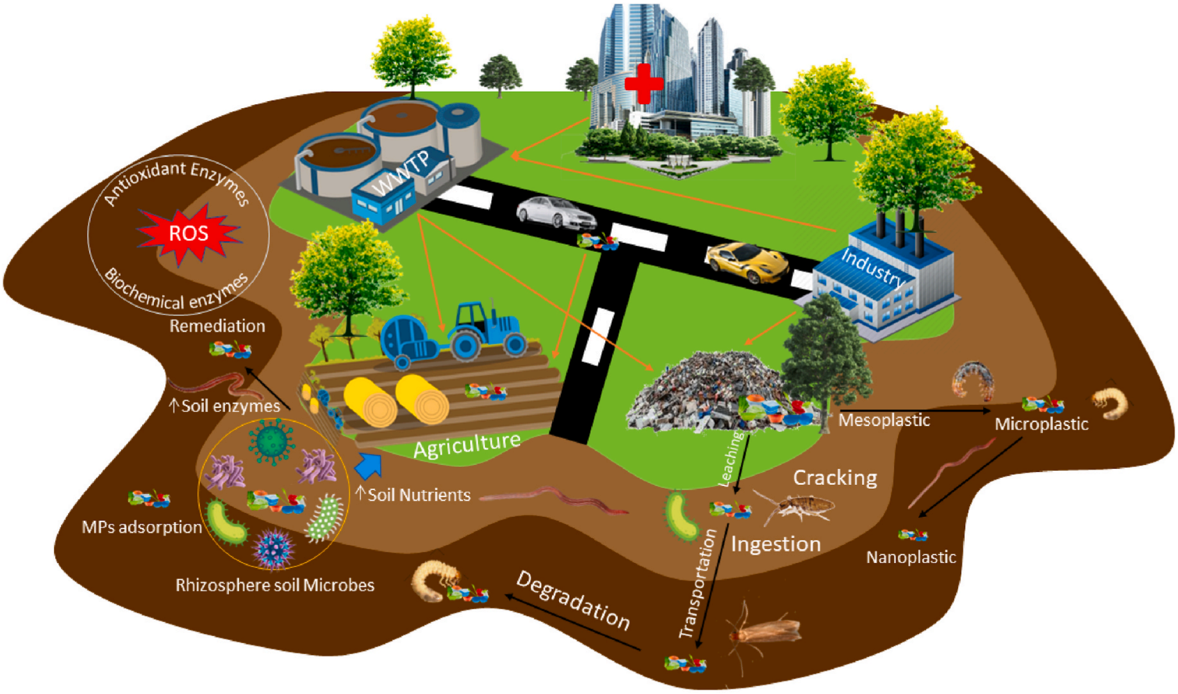

Fig. 1. Schematic representation of plastic sources and their behaviour on soils. *Figure courtesy of Imran Azeem (College of Resources and Environmental Sciences, China Agricultural University, Beijing, China).*

prevalence, source, possible hazards, impact on different soil communities or migration through the soil profile, are still understudied and require more attention (Chang et al., 2022; Sajjad et al., 2022; Ya-di et al., 2022).

Furthermore, MP chemical composition significantly influences their characteristics, including toxicity, density, and ability to degrade. High molecular polymers (LDPE, PS or PP) are the main component of MP formulations, with plasticizers, stabilizers, and colouring agents as additive components. Because of this, the soil's physical, chemical, and biological qualities might be altered due to the variety of potential compositions. The majority of MP have a hydrophobic surface, which has the potential to alter water holding capacity, transport, and availability in soil. The density of MP is one of the significant factors. Since the density of most MP is often lower when compared to that of soil, adding MP to the soil will always decrease the soil's bulk density (de Souza Machado et al., 2018b, 2019; Chia et al., 2021, 2022). However, the breakdown process of MP may lead to the release of poisonous and dangerous compounds or pollutants that have been adsorbed onto them (Rodríguez-Seijo et al., 2019; Dai et al., 2022; Meng et al., 2021), which will have a significant impact on the soil chemical and biological characteristics, mainly providing a direct threat to soil biota. Microplastics have been shown to impact aquatic organisms significantly. Still, it is less evident if and how they might influence diverse taxa within a soil community or whether these effects can cascade via soil food webs (Lin et al., 2020; Zhang et al., 2020b; Dai et al., 2022; Okoffo et al., 2021; Dissanayake et al., 2022). This issue seems of particular interest in agroecosystems because agricultural plastics can be easily contaminated by several agrochemicals such as fungicides (e.g., Cu), pesticides, insecticides, etc. (Rodríguez-Seijo et al., 2019; Dai et al., 2022).

Soil fauna is numerous, varied, and interesting in that they contribute to soil ecosystems in many ways, including their unique eating habits and survival techniques (Lavelle, 1996; Wolters, 2001). In general, soil fauna is categorized into four classes based on their body width: (1) microfauna, e.g., small mites, nematodes, rotifers, tardigrades, and copepod crustaceans (20–200 μm), (2) mesofauna with body size in between 200 μm and 2 mm (e.g., springtails and mites), (3) macrofauna such as earthworms, gastropods, and myriapods having body size between 2 mm and 20 mm, (4) megafauna are the largest species of soil fauna with a body size greater than 20 mm (e.g., moles, snails, etc.) (Petersen and Luxton, 1982; Menta, 2012). Meso- and macrofauna, such as mites, springtails and earthworms, are well-known to play a crucial role in maintaining soil quality; nevertheless, the effect of MP on these critical creatures may represent a risk to agroecosystem function (George et al., 2017; Dissanayake et al., 2022; Wang et al., 2022b).

Current research has focused chiefly on some model organisms, such as soil microfauna and mesofauna. Generally, soil fauna, including earthworms, snails, collembolans, and nematodes, have all been shown to be negatively impacted by MP in recent research (e.g., Huerta Lwanga et al., 2017a, 2022; Rodríguez-Seijo et al., 2017, 2018; Zhu et al., 2018b; Ju et al., 2019; Song et al., 2019; Kim et al., 2020a,b; Selonen et al., 2020; Shafea et al., 2022). For instance, when soil fauna ingests MP, it may cause adverse consequences at reproductive and oxidative stress levels (e.g., Rodríguez-Seijo et al., 2018, 2019; Cheng et al., 2020; Lackmann et al., 2022; Shafea et al., 2022; Wang et al., 2022b), disruption of the symbiotic microbiota in the gut of soil fauna (Zhu et al., 2018b; Ju et al., 2019), affect their growth and development restricting the mobility of soil microarthropods by clogging soil pores (Kim and An, 2019). More attention should be paid to the impacts of MP on the other micro- and mesofauna of the soil (Rodríguez-Seijo and Pereira, 2020) since there are very limited studies on how MP impact soil organism less than 2 mm in size.

The existing knowledge on the impacts of MP on soils (physicochemical properties and structure) and its associated micro- and mesofauna communities (above and below ground) is still insufficient to address the threats to the terrestrial environment effectively. In this sense, most of the MP-related publications were devoted to aquatic environments (60%), especially to marine environments; 16% of them dealt with sediments, and less than 20% related to terrestrial ecosystems (e.g., sources, distribution, soil properties, ecotoxicological assays, etc.) (Fig. 2a). From the soils and soil organisms, more than 55% of publications have been related only to earthworms, but related research to meso- and micro-fauna has been increasing in the last few years (Fig. 2b).

In this regard, the current review has been designed to shed light on the environmental fate of MP in soils and understudy the ecotoxicological consequences these materials have on the behaviour of soil microfauna and mesofauna. This review paper provides a comprehensive and insightful analysis of current investigations on how MP pollution can modify the structure and functioning of soil micro- and mesofauna at different plastic concentrations. Furthermore, this paper highlights the role of micro- and mesofauna as plastic transporters and degradation in soil systems. Finally, we briefly discussed some potential future directions for research, including new methodologies, protocoals, and approaches that could be used to further investigate the impact of microplastics on soil organisms, as well as any other areas where further research is needed.

2. Microplastics impact on soil microfauna

The two most important microfauna groups are the protozoa and nematodes, usually linked to sandy soils and depend on a thin water film on the soil surface for their development. They have an essential role in microbial diversity and functional stability, soil organic carbon cycle or availability of nutrients for plants and sometimes with a role in the bioremediation of contaminated areas (Rillig and Bonkowski, 2018;

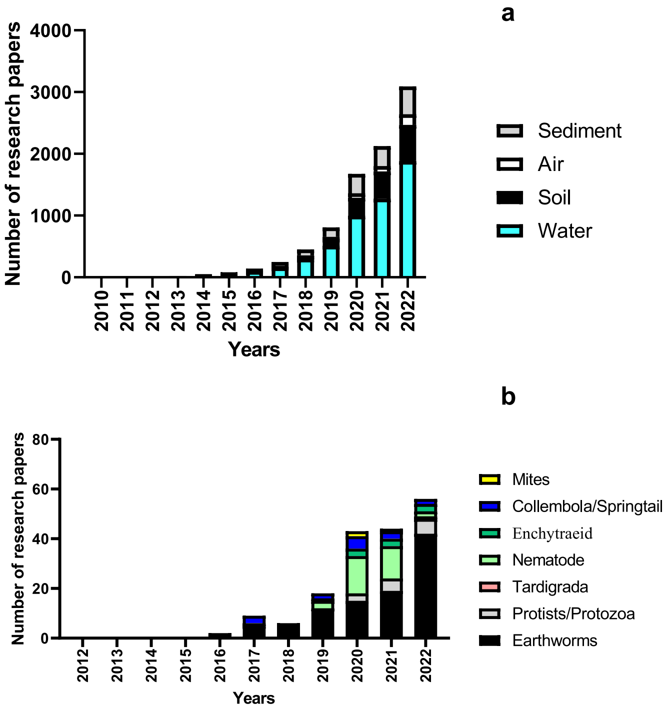

Fig. 2. Global scientific production on microplastic contamination under different ecosystems (aquatic and terrestrial ecosystems, sediments and air environment) (a) and with soil organisms (b). The bars represent the number of publications (scientific articles, but review papers were excluded) published between 2010 and 2022. A literature survey was performed using the following keywords: "soil", "nematode", "worm", "earthworm" "protist", "tardigrada", "collembola", "springtail", "microfauna", "enchytraeid, "potworm" and "mites" (Scilit, ISI® Web of Knowledge and Scopus® and Scopus® databases sources). Papers published up to December 2022.

Alali, 2019; Wang et al., 2022b; Wu et al., 2022).

2.1. Soil protists

Protists are essential for soil biodiversity and function (Rillig and Bonkowski, 2018 Geisen et al., 2020; Wu et al., 2022). They serve significant roles in microbial food webs and in controlling soil fertility and plant development as consumers of bacteria, fungi, and other microscopic eukaryotes (Chandarana and Amaresan, 2022; Chang et al., 2022). Protists are plentiful and diverse, and they are widely distributed in soil (Wu et al., 2022). They predominantly stimulate plant development and health via nutrient cycling, grazing, and activation of bacterial genes required for plant growth and phytopathogen suppression. Besides, soil protists can be employed as biological sensors of soil contamination and with a different sensitivity than soil bacteria (Rillig and Bonkowski, 2018; Kanold et al., 2021; Zhu et al., 2021; Wu et al., 2022), because they are critical eaters of bacteria in soils and may be crucial carriers for the transport of MP into the soil food chain (Rillig and Bonkowski, 2018). In this sense, Kanold et al. (2021) reported for the first time that soil protists can consume MP, and keep them within their food vacuoles under low concentrations (<0.1% w/w). Still, protist abundance declines with increasing plastic concentrations (up to 1% w/w), being this situation an ecological issue due to the important role of soil protists in the transport and uptake of MPs in the soil food web (Kanold et al., 2021) (Table 1). Zhang et al. (2022b) reported similar results to be indicated by Kanold et al. (2021) for *Dictyostelium discoideum* (Raper, 1935), with adverse impact on fitness and development, including nutrient and energy metabolism and nano- and microplastic ingestion through phagocytosis. Still, they packed and excreted them during slug migration. More interesting is that Zhang et al. (2022b) also observed a potential PS biodegradation due to protist feeding activity.

Furthermore, Zhu et al. (2021) reported that the structure and composition of soil protist communities were highly affected under MP/NPs exposures, while fungi and bacteria communities were partially affected. In addition, MP/NP co-contaminated with arsenic (As), increased the effects of As on protistan soil communities (Table 1). Besides, Xiang et al. (2022) showed that soil mesofauna (collembola and potworms) can alter the plastisphere soil community (bacteria, fungi, and protists) when exposed to PE for 60 days. Protist time-decay curves (total and abundant taxa) exhibited a bigger reduction without soil mesofauna than with mesofauna, whereas bacterial and fungi showed the opposite trend. This issue reinforces the need for holistic approaches to the problem of plastic pollution. Despite these studies, the knowledge between soil protists and MPs is largely unknown.

2.2. Tardigrada

Tardigrades include several ecologically important and well-studied species, feeding on microbes and detrital particles (Büks et al., 2020). Tardigrades are tiny invertebrates that need a thin layer of water surrounding their body to function normally. They are widely recognized, however, for their capacity to endure periods of desiccation and other adverse environmental circumstances. Consequently, tardigrades may live worldwide in many marines, freshwater, and wet terrestrial settings (Blagden et al., 2020). Soil microfauna, including tardigrades, has limited dispersion because their mobility is constrained to water-rich settings Sparse field studies in semi-aquatic conditions have shown minimal uptake of MP fibres by tardigrades; nevertheless, non-exhaustive data are available for terrestrial soils. According to Corinaldesi et al. (2022), PS and PE can increase the ecological impacts on meiofaunal assemblages of Tardigrada collected from beach sediments (Table 1). As indicated for soil protists, more studies are needed with tardigrades.

2.3. Rotifers

Rotifers are key components in freshwater, coastal marine ecosystems and wet soils. They are utilized in ecotoxicology investigations as model animals (Xue et al., 2021). Rotifers are essential in aquatic and terrestrial ecosystems' biogeochemical cycles and trophic dynamics (Alvarado-Flores et al., 2021; Robeson et al., 2011). Several studies have been reported for aquatic rotifers (e.g., Manfra et al., 2017; Beiras et al.,

Table 1
A summary of the effect of microplastics on tardigrades and soil protist communities.

Specie testing	Polymer type	Size	Concentration	Exposure conditions	Observed endpoints	Reference
Protists						
Free-living ciliated protists	Green, fluorescent amino formaldehyde microspheres	1–5 µm diameter	0, 0.1, 1 %w/w	Microcosm experiment (petri dish) for 14 days	Keep MP within their food vacuoles at low concentrations (0.1% w/w), and ingestion causes a decline in protist abundance with increasing concentrations (1% w/w)	Kanold et al. (2021)
	PE + As	200 nm (NP) and 200 µm (MP)	0, As (40 mg kg^{-1}), MP (2000 mg kg^{-1}), As + MPs (40, 2000 mg kg^{-1}, respectively), NP (200 mg kg^{-1}), As + NPs (40, 200 mg kg^{-1}, respectively)	Pot experiment (*Lactuca sativa* L.) for 75 days.	The composition and structure of the community and the relative abundance were affected. Plastic presence can increase the adverse effects of As	Zhu et al., (2021)
Soil plastisphere community (bacteria, fungi, and protists)	PE	±1.2 mm	1%	Microcosm experiment during 60 days with collembola, potworms and soil plastisphere	Protist time-decay curves (total and abundant taxa) exhibited a bigger reduction without soil mesofauna than with mesofauna, whereas bacterial and fungi showed the opposite trend.	Xiang et al., (2022)
D. discoideum	PE + PS	Nano- (20 and 100 nm) and microplastics (1000 nm)	25, 250, and 2500 mg kg^{-1} on w/w of PS/water	Agar plates and soil incubation.	Adverse impact on fitness and development, including nutrient and energy metabolism. Nano- and microplastic ingestion through phagocytosis but packed and excreted during slug migration—possible PS biodegradation.	Zhang et al., (2022b)
Tardigrada						
Not mentioned	PE, PP, PVC, PET	20–1000 µm	1000 Particles L^{-1}	Microcosm experiment. Beach sediments	Increase the ecological impacts on meiofaunal assemblages	Corinaldesi et al., (2022)

Polyethylene (PE), Polypropylene (PP), Polyvinyl chloride (PVC), Polyethylene Terephthalate (PET), Polystyrene (PS), Nanoplastic (NP).

2018; Venâncio et al., 2019), especially with *Brachionus plicatilis* (Müller, 1786) and *B. koreanus* , where it was found that the poisonous effects on life span, fertility and oxidative stress impacts (Jeong et al., 2016; Sun et al., 2023; Sui et al., 2022), due to having relatively poor food particle selection abilities as filter-feeding organisms (Jeong et al., 2016; Jiang and Li, 2020; Drago and Weithoff, 2021; Sun et al., 2023). Studies with soil rotifers are scarce, and the probable impacts will be indicated for aquatic species. However, Büks et al. (2020) indicated that data with aquatic species should be carefully transferred to soil environments since soil rotifers are aquatic organisms living in water films and water-filled pores.

2.4. Soil nematodes

Soil nematodes are now commonly employed to assess soil health since they regulate the number of other soil organisms or convert soil mineralize into forms that plants can use. Furthermore, soil nematodes improve soil health by feeding secondary species beneficial to the soil (for example, earthworms) or by feeding on organisms that cause illness in soils (Gao et al., 2020; Biswal, 2022). Soil nematodes in the soil environment might suffer adverse consequences because of soil plastic pollution (Table 2). In general, (micro)plastic exposure can reduce soil nematode reproduction, nematode abundance, neurotoxicity, oxidative stress effects, and change in the community composition (Kim et al., 2020b; Lin et al., 2020; Mueller et al., 2020; Schöpfer et al., 2020; Yu et al., 2022) (Table 2). According to Kim et al. (2020b), soil MP pollution caused by polyacrylicnitrile (PAN) and PET reduces soil nematode reproductive potential, while HDPE, PP, PS and LDPE had less or non-toxicity. Schöpfer et al. (2020) had similar results when exposed to LDPE, PLA and PBAT, in this case, nematodes had fewer offspring for all plastic types. This decrease in soil nematode reproductivity might be due to the toxicity of these MPs (Wang et al., 2021), mainly due to extractable additives and plastic shapes (fibres) (Kim et al., 2020b). Furthermore, soil MP contamination, which resulted in reduced or decreased soil nematode population and offspring (e.g., Lin et al., 2020) (Table 2), might be attributed to several processes, including MP ingestion and habitat modification by MPs (Ju et al., 2019). Wood (2020) indicated that nematodes that regularly eat on soil might eventually suffer from digestive tract blockage and die after feeding in soil polluted with MP, although plastic ingestion is species-specific due to buccal cavity size since nematodes cannot ingest MP > 3.4 μm (Fueser et al., 2019; Mueller et al., 2020; Wang et al., 2022c) and usually, toxicological effects are exacerbated under 1 μm (Lei et al., 2018b).

Even if soil pollution with MP is harmful to nematode survival, the concentration of MP in soils will determine this; for example, Fajardo et al. (2022) discovered that exposing nematodes to 0.1% w/w PE microbeads contaminated with different organic contaminants (ibuprofen, sertraline, amoxicillin and simazine), did not affect nematode proliferation in soils. However, these results can contradict other reports where MPs adversely affect nematode communities. In this sense, Fajardo et al. (2022) attributed the interaction of soil biotic and abiotic components with different organic contaminants can decrease their impact. In addition to Fajardo et al. (2022), other studies have been carried out with co-contaminated plastics (Dong et al., 2018; Qu et al., 2019; Li et al. 2020, 2020b), although indicated contradictory results.

Finally, plastic contamination can alter soil nematode communities, usually plastic-type dependent. While Lin et al. (2020) observed that LDPE exposure under field-trial had an adverse impact on soil nematode composition, Mueller et al. (2020) observed that *A. nanus* populations grew faster in the presence of PS, whereas *C. elegans* and *P. acuminatus* showed slower reproduction (Mueller et al., 2020; Shafea et al., 2022) (not shown in Table 2). These investigations, however, are more exploratory, and we need real-world studies to back this up.

3. Plastic pollution impacts soil mesofauna

The widespread use of different types of plastic stuff in our daily life necessitates the study of the impacts of MP on living organisms, especially soil organisms, which is poorly known. Soil mesofauna, which typically contains Acari, Collembola, Proturans, Diplurans and Enchytraeidae, is an environmental-sensitive group of soil invertebrates with essential roles in soil functions such as breakdown of organic matter and nutrient recycling, stimulation and control in soil microorganisms' abundance (George et al., 2017; Büks and Kaupenjohann, 2020). Therefore, soil mesofauna has been considered a well-deserved indicator to study the environmental changes caused by external materials, e.g., MP, in the soil ecosystem. In contrast to how much research has been conducted to investigate the effect of MP on aquatic ecosystems, the perception of the interaction between soil mesofauna and MPs remained poor (Büks and Kaupenjohann, 2020). In the recent decade, some studies tried to fill the gap in our knowledge and the possible impacts of MPS on soil ecosystems by using soil organisms, especially soil mesofauna organisms, such as collembolans, as common study model organisms (Table 3).

3.1. Plastic contamination as critical environmental stress and soil mesofauna

The gap in our knowledge of ecotoxicology and risk assessment of MPs on soil mesofauna can be filled by studies about toxicity mechanisms of MPs in soil ecosystems and prediction of the exposure route of study model Collembola *Folsomia candida* (Willem, 1902), and Enchytraeidae *Enchytraeus crypticus* (Westheide and Graefe, 1992) to MP, which has been tested by investigating the impacts of MPs on their gut microbiota, growth, reproduction, and isotope turnover (e.g. Zhu et al., 2018b a,b). But specifically, because of MP effects on non-target species, a change occurs in their gut microbial community that induces changes in isotopic fractionation and antibiotic resistance gene, which furthermore shows the profound influence of MPs on soil organisms and soil food web (Zhu et al., 2018b; Ju et al., 2019; Lahive et al., 2019; Xiang et al., 2019; Kim and An, 2020; Ma et al., 2020b; Pflugmacher et al., 2020; Ding et al., 2022).

In general, plastic exposition to collembola or enchytraeid impacted less mobility, changes in feeding rates and growth, avoidance of MP-contaminated areas, and reduced reproduction (Table 3). Different plastic polymers, both conventional and biodegradable (PP, PE, PS, PLA or PBS), from micro-to nanoplastics, which are widely used in our daily life, has been recently studied to understand its likely harmful effects on microarthropod communities (Abundance and Diversity), e.g., Collembola *F. candida*, Prostigmata, Mesostigmata *Amblyseius swirskii* (Athias-Henriot, 1962), Astigmatism, and Oribatid mites *Oppia nitens* (Koch, 1836), Enchytraeidae *E. crypticus*, as a key role player in decomposers food web (e.g., Barreto et al., 2020; Selonen et al., 2020, 2021, 2023; Huang et al., 2023) (Tables 4 and 5).

In any case, exposure of mesofauna to MP and nanoplastics is a soil health issue due to the several implications of the organisms on soil functions (George et al., 2017; Büks and Kaupenjohann, 2020; Mendes, 2021). In general, many studies have shown adverse effects at several levels, from avoidance of plastic-spiked soils to impacts on reproduction, growth, oxidative stress and/or gut microbiota changes (Tables 3 and 4). Enchytraeids have a vital role in soil mineralization and can ingest soil and MP as fibres, resulting in significative impacts on reproduction, body size and number or juveniles (e.g., Lahive et al., 2019; Selonen et al., 2020, 2021; Pflugmacher et al., 2020; Yang et al., 2022a). Besides, adverse effects can be increased when plastics act as carriers of inorganic and organic contaminants (nanomaterials, pesticides, insecticides, car tyre degradation, etc.), since MP can increase the toxicological effects of these contaminants or *vice versa*. Joint contamination can increase gut microbiota changes (e.g., Ding et al., 2020; Tourinho et al., 2021; Selonen et al., 2021; Ma et al., 2020a) (Table 3).

Table 2
An overview of the effect of nanoplastics and microplastics on nematodes.

Specie testing	Polymer type	Size	Concentration	Exposure conditions	Observed endpoints	Reference
Nematodes						
Group of nematodes bacterivores	PP	<250 µm	0, 0.5, 1, 2%, w/w	A pot experiment with corn.	Negatively affected soil nematode diversity and ecological functioning	Yang et al., (2022a)
Caenorhabditis elegans (Maupas, 1900)	Fluorescently labelled PS	100–1000 nm	100 µl suspension of 1.0×10^9 ml^{-1} of 0.5 µm and 1.0×10^8 ml^{-1} of 1.0 µm microspheres in S-basal buffer	Agar plates. 30 min.	Uptake and accumulation in the intestine and pharynx.	Kiyama et al., (2012)
	PA, PE, PP, PVC Fluorescently labelled PS	~70 µm 0.1, 1.0 and 5.0 µm	MP suspension in K-medium (32 mM L^{-1} KCl, 51 mM L^{-1} NaCl) was added to the nematode growth medium at different concentrations (0.5, 1.0, 5.0 and 10.0 mg m^{-2})	Agar-padded slide. 2 days.	Inhibition of growth, survival and reproduction; decreased intestinal calcium levels, microplastic accumulation in the intestine, and oxidative stress (increased expression of Glutathione S-transferase 4).	Lei et al., (2018a)
	PS	100, 500 nm (NanoPS) and 1, 2 and 5 µm (MP)	1 mg L-1	3 days	The lowest survival rate, decreased body length and shortest lifespan for those exposed to the 1.0 µm group	Lei et al., (2018b)
	Nano-PS	50 and 200 nm	17.3 mg L^{-1} and 86.8 mg L^{-1}	Agar-padded slide. 1 day.	Inhibition of locomotion and reproduction Induction of oxidative stress (ROS production). Changes in energy metabolism (reduction of TCA cycle intermediates, lactic acid and glucose). Uptake and accumulation of nanoplastics in the intestine	Kim et al., (2019)
	HDPE, PET, PP, PS, LDPE, PAN	<250–1000 µm	0.001–1% w/w	Acute toxicity test (24 h)	Decrease Nematode offspring. PET and PAN show the highest toxicity—less toxicity under HDPE, PP and PS treatments. LDPE treatment was not toxic. Acute toxicity was mainly attributed to the extractable additive	Kim et al., (2020b)
	TiO_2-Nano-PS	108.2 ± 4.5 nm	0.01, 0.1, or 1 µg L^{-1} by 1% solid suspension in water	Agar-padded slide. 1 day.	Inhibition of locomotion and induction of intestinal ROS production	Dong et al., (2018)

Species testing	Polymer type	Size	Concentration	Exposure conditions	Observed endpoints	Reference
Nematodes community	LDPE	0.3–400 µm	+5, +10 and + 15 g m^{-2}	Field experiment for 287 days	Nematode abundance and Changes in the community composition are significantly affected by microplastic additions	Lin et al., (2020)
C. elegans	LDPE, PLA, PBAT	LDPE: 57 ± 40 µm. PLA and PBAT: 40 ± 31 µm	0, 1, 10, and 100 mg MP L^{-1}	Agar plates (~6 days)	Nematodes had fewer offspring. The decline was independent on the plastic type.	Schöpfer et al., (2020)
	PS and PS-COOH	1.018 (PS) and 1.021 (PS–COOH) µm	0.1–100 µg L^{-1}	Exposure for 24 h	PS-COOH is highly neurotoxic, including damage to neurones.	Yu et al., (2022)
	PE microbeads and different organic contaminants (ibuprofen, sertraline, amoxicillin, and simazine)	212–300 µm	dose of 0.1% w/w of MPs	Exposure for 4 and 30 days	Did not affect growth, reproduction, or survival.	Fajardo et al., (2022)
C. elegans, *Acrobeloides nanus* (de Man, 1890), *Plectus acuminatus* (Bastian, 1865)	PS microspheres	1 µm	Suspensions 10^{-7} PS beads ml^{-1}	Nematode growth gelrite. 49 days.	Ingestion of 1.0-µm PS beads by three nematode species. Significant differences in population growth.	Mueller et al., (2020)
C. elegans, *A. nanus*, *Panagrolaimus thienemanni* (Hirschmann, 1952), *P. acuminatus*, *Poikilolaimus regenfussi* (Sudhaus, 1980)	PS beads	>0.5, 1, 3 and 6 µm	PS suspension. 10^7 and 3×10^6 PS beads ml^{-1}	4, 24 and 72 h	Ingestion by nematodes with a buccal cavity, and species-specific. Influence of concentration and exposure on ingestion.	Fueser et al., (2019)

Species testing	Polymer type	Size	Concentration	Exposure conditions	Observed endpoints	Reference
C. elegans	NanoPS SiO_2-NPs, Al_2O_3-NPs and TiO_2-NPs	30 nm	0, 0.1, 1, 10 and 100 µg L^{-1}	Not mentioned	NP is more toxic than contaminated by metal oxides	Li et al., 2020a
	NanoPS + chlordane and hexachlorocyclohexane	100 nm	NanoPS: 1.0 mg L^{-1}, contaminants (0.1–10 mg L-1)	Exposure for 72 h	Increased toxicity under combined exposure (lifespan, increased oxidative stress)	Li et al., (2020b)
	NanoPS	20 and 100 nm	0.1–100 µg L^{-1}	Exposure for 6.5 days	Smaller size have more toxicity (transgenerational toxicity) than the bigger size.	Liu et al., 2021

(continued on next page)

Table 2 (*continued*)

Species testing	Polymer type	Size	Concentration	Exposure conditions	Observed endpoints	Reference
	NanoPS	100 nm	1–100 μg L^{-1}	Exposure for 6.5 days	Activation of mitochondrial unfolded protein response	Liu and Wang (2021)
	NanoPS, amino-modified NanoPS	35 nm	1, 10, 100, and 1000 μg L^{-1}	Exposure for 2 days	Damage on gonad development and reproductive capacity. Amino-modified NanoPS showed higher toxicity than pristine PS.	Qu et al., (2019)
	NanoPS	100 nm	0, 1, 10, 100, 1000, and 10,000 μg L^{-1}	Exposure for 4.5 days	Transgenerational toxicity on concentrations >100 μg L^{-1}. Probable translocation into the gonad.	Zhao et al., (2017)
	PS	1 μm	0, 0.1, 1, 10, and 100 μg L^{-1}	Exposure for 72 h in liquid solutions	Adverse physiological effects. Oxidative stress response on higher concentrations. Intestine accumulation.	Yu et al., (2020)

Nanopolystyrene (NanoPS), Polyethylene (PE), low-density polyethylene (LDPE), Polystyrene (PS), biodegradable polymers polylactide (PLA), Poly(butylene adipate-*co*-terephthalate) (PBAT), carboxyl-modified polystyrene microplastics (PS–COOH).
Nanopolystyrene (NanoPS), Polystyrene (PS).

Similar effects are also reported for collembolans, with adverse effects on reproduction and juveniles' growth, oxidative stress, avoidance and/or decreased locomotion, etc. (Table 4), although collembola can act as passive plastic transporters on soil matrix (e.g., Maaβ et al., 2017; Zhu et al., 2018b) and increase the potential toxicity to other soil (micro-)organisms. As indicated for enchytraeids, plastic ingestion can modify gut microbiota (e.g., Zhu et al., 2018a; Ju et al., 2019). Plastic mite exposure showed different effects according to plastic shape and size (Table 5). While fibres exposure didn't significantly affect reproduction and abundance when exposed to PP and PES (Barreto et al., 2020; Selonen et al., 2020), exposure to PE and PS under bigger fragments showed detrimental effects on the abundance of mites (Stamatiadis and Dindal, 1990). However, more studies are needed.

Although many studies have focused on the ecotoxicological impacts on soil micro and mesofauna, these studies have usually focused on single contamination with a single organism species instead of an organism community or mixed contamination (Wang et al., 2022b; Huang et al., 2023). In this sense, some studies have assessed the impacts of plastic debris on soil micro- and mesofauna communities under field conditions (Barreto et al., 2020; Lin et al., 2020; Brown et al., 2021; Xiang et al., 2022; Huang et al., 2023). In general, short-term exposure (30-130 d) does not harm the abundance, diversity, or structure community (Barreto et al., 2020; Huang et al., 2023). However, Lin et al. (2020) reported some differences in soil abundance and diversity under long-term exposures (287 d), and Brown et al., 2021 also suggested that long-term pollution (plastic accumulation in soils during decades) could be more harmful than short-term pollution. A probable explanation can be related to the plastic size that was larger than those that certain soil fauna species can ingest (e.g. edible size for springtails should be less than 66.0 μm, Kim and An, 2020), but the entrance of plastic particles in the soil food web by ingestion of organisms is certain (Stamatiadis and Dindal, 1990; Selonen et al., 2020; Amorim and Scott-Fordsmand, 2021; Hernández-Gutiérrez et al., 2021; Razzak et al., 2022).

Besides, tire tread particles made of synthetic rubber polymers may contaminate the environment with a high concentration of potentially toxic elements (Cd, Cr, Pb, Zn, etc.) and Polycyclic Aromatic Hydrocarbons and decrease the survival and reproduction rate of *E. crypticus* (Ding et al., 2020; Selonen et al., 2021), and adversely affect its gut microbial communities by enriching microbiota causing aggregation of opportunistic pathogens (Ding et al., 2020). Similar effects were also observed for *F. candida* when exposed to tire particles (Selonen et al., 2023). Also, plastics can carry co-contaminants such as agrochemicals (insecticides, antibiotics, etc.). Plastic presence can increase the toxicity of these organisms, as reported by *E. cripticus* when exposed to tetracycline (e.g., Ma et al., 2020a, 2020b; Yang et al., 2022b), or for *F. candida* with tetracycline and chlorpyrifos (e.g., Xiang et al., 2019; Selonen et al., 2023) with increased antibiotic resistance in exposition to mixed contamination (Xiang et al., 2019).

Plastic pollution and the presence of MPs in every ecosystem is globally becoming an environmental issue, which certainly has a close relationship with the soil mesofauna life cycle in critical eras and regions of the earth. In this case, it can be stated that there is evidence of the presence of MPs in the gut of Collembola *C. antarcticus*, a central component in the Antarctic terrestrial food web (Bergami et al., 2020). It shows that they reached one of the most remote regions on earth. This can be considered a significant threat to aquatic and terrestrial polar biota (Bergami et al., 2020; Rota et al., 2022), which are already under the stress of intense climate change (Rota et al., 2022). Additionally, during the Covid-19 pandemic, improper disposal of face masks, mainly produced by PP, has been evidenced in an experimental set-up to inhibit reproduction and stunt the growth of collembola species (Kwak and An, 2021).

In this sense, more long-term studies, with nanoplastics size (<1 μm) but especially considering the maximum edible size and the potential role of nano- and microplastics as contaminants carriers should also be assessed (Barreto et al., 2020; Ding et al., 2020; Pérez-Reverón et al., 2022; Wang et al., 2022b). In addition, sometimes, comparison between studies is not easy since several differences between the studies' methodology (Büks and Kaupenjohann, 2020; Wang et al., 2020b) and other indirect factors (e.g., global change) that can impact soil biota and ecosystem processes (Barreto et al., 2020).

4. Role of micro- and mesofauna as plastic transporters and plastic degraders

4.1. Plastic transporters

Gravity, wind erosion and water infiltration are essential in plastic transport in the soil as abiotic processes. Still, biotic processes, such as root growth and fauna activities, have a crucial role in plastic movement through the soil matrix since abiotic movements are also influenced by biotic processes (Rillig et al., 2017; Helmberger et al., 2019; Li et al., 2021; Pérez-Reverón et al., 2022). In this sense, the role of macrofauna, especially earthworms, as MP carriers through the soil profile via bioturbation, ingestion or cutaneous adhesion and their role in the degradation of plastic debris in the soil and their conversion into micro- and nanoplastics has been described in recent years (e.g., Huerta Lwanga et al., 2017a,b; Heinze et al., 2021; Helmberger et al., 2019,2021; So et al., 2022; Rillig et al., 2017). Similar effects were also reported for other soil organisms, such as ants, which role as plastics transporters cannot be neglected (Rillig and Bonkowski, 2018; Liu et al., 2022). However, the plastic movement and transport are strongly dependent on polymer chemistry, adsorbed contaminants, and size, both from the organism and plastic size (Rodríguez-Seijo et al., 2019; Huerta Lwanga et al., 2022; Dai et al., 2022; Luo et al., 2023), and the role of micro- and mesofauna in these processes has been less studied and requires attention as highlighted by different researchers (Maaβ et al., 2017; Rillig et al., 2017; Rodríguez-Seijo and Pereira, 2020; Sánchez-Hernández,

Table 3
An overview of the effect of nanoplastics and microplastics on potworms.

Specie testing	Polymer type	Size	Concentration	Exposure conditions	Observed endpoints	Reference
Enchytraeid						
E. crypticus	PA	30 µm	1000 mg kg^{-1} (dry weight)	Agriculture soil. 21 days.	No mortality. Increased reproduction.	Ma et al., (2020a)
	PVC			Agriculture soil. 21 days.	No mortality. Significantly reduced reproduction	
	PA + TC		1000 mg kg^{-1} (PA) and 20 mg kg^{-1} soil (TC) (dry weight)	Agriculture soil. 21 days.	No mortality. Significantly reduced reproduction. Tetracycline and microplastics disturbed the microbial community in *E. crypticus.* Increased TC bioaccumulation.	
	PVC + TC		1000 mg kg^{-1} (PVC) and 20 mg kg^{-1} soil (TC) (dry weight)	Agriculture soil. 21 days.	No mortality. Significantly reduced reproduction. Tetracycline and microplastics disturbed the microbial community in *E. crypticus.* Increased TC bioaccumulation.	
	PES	12 μm–2.87 mm to 4–24 mm	0, 0.02, 0.06, 0.17, 0.5 and 1.5% w/w	LUFA soil type no. 2.2.21 days	Survival was slightly decreased only at moderate fibre concentrations (0.17–0.5%) Long fibres in soil negatively affected the reproduction at all concentrations except for 0.06%	Selonen et al., (2020)
	Tire particles*	80–110 µm	0, 0.02, 0.06, 0.17, 0.5 and 1.5% w/w	LUFA soil type no. 2.2.21 days	Slight decrease in the reproduction of *E. crypticus* was not dose-dependent.	Selonen et al., (2021)
	PS	50–100 nm	Eq. 1000 mg kg−1 (TC 10 mg kg-1, 4 Ml nanoscale PS solution (2.5% w/v))	Petri dish + Oats contamination. 14 days.	No mortality	Ma et al., (2020b)
	PS + TC	50–100 nm			No mortality. Loss weight. PS and TC together reversibly perturb the microbial community of *E. crypticus*. TC bioaccumulation	
E. crypticus	PA	13–18 and 90–150 µm	20, 50, 90 and 120 g kg^{-1}	LUFA soil type no. 2.2.21 days	No effects on survival. Reproduction significantly reduced. Ingestion of PA particles.	Lahive et al., (2019)
	PA	63–90 µm	90 g kg^{-1}		No effects on survival. Reproduction significantly reduced. Ingestion of PA particles.	
	PVC	106–150 µm	90 g kg^{-1}		No effects on survival. Reproduction significantly reduced.	
	Tire particles*	13–1400 µm	0, 0.0048%, 0.024%, 0.12%, 0.6%, and 3% of dry soil weight	Fluvo-aquic soil. 21 days	Adverse effects on survival, reproduction and disturbed the microbiota	Ding et al., (2020)
	HDPE	4 mm	0, 2%, 4% or 8% w/w	Turf-free soil (20% lingo fibres, 35% cocopeat washed, 10% spelt fermented, and 35% substrate compost). 2	Avoided plastic-spiked soil. Slighty mortality at higher concentrations (8%) Oxidative stress response (an increase of catalase and glutathione S-transferase activities)	Pflugmacher et al., (2020)
	PS fibers + Ag nanoparticles	50–3000 µm	PS fibers (0.01% dry weight) + Ag nanoparticles (32, 100, 320, 1000, 3200 mg Ag kg^{-1})	LUFA soil type no. 2.2.21 days	No significative effects on reproduction. Microplastic fibre influences on Ag toxicity (Slighty uptake and bioaccumulation of Ag at higher levels with PS).	Tourinho et al., (2021)
	PES	12–2870 µm	0.02%, 0.06%, 0.17%, 0.5% and 1.5% w/w via soil and food		Ingestion and excretion	Mendes (2021)
	Nano-PS	100 nm	Nanoscale PS (eq. 1000 mg kg^{-1})	Agricultural soils. 21 days	No effects on reproduction or body weight. NanoPS disturbed the gut microbiome,	Yang et al., (2022b)
	Nano-PS + TC	100 nm	(TC 20 mg kg^{-1}, L nanoscale PS (eq. 1000 mg kg^{-1}))	Agricultural soils. 21 days	Highest body weight. Significative effects for reproduction. NanoPS disturbed the gut microbiome and enhanced the toxicity of TC, and promoted antibiotic resistance genes enrichment.	

Polyamides (PA), Polyester (PES), Polyvinyl chloride (PVC), Polystyrene (PS), Tetracycline (TC). *Tire particles (usually generic reference, but they're a mixture of synthetic rubbers including styrene-butadiene rubber (SBR), butadiene rubber (BR), and butyl rubber (IIR)) (Ding et al., 2020; Selonen et al., 2021, 2023).

High-density Polyethylene (HDPE) Nanopolystyrene (NanoPS), Polyamides (PA), Polyester (PES), Polyvinyl chloride (PVC), Polystyrene (PS), Tetracycline (TC). *Tire particles (usually generic reference, but they're a mixture of synthetic rubbers including styrene-butadiene rubber (SBR), butadiene rubber (BR), and butyl rubber (IIR)) (Ding et al., 2020; Selonen et al., 2021, 2023).

2021). Microarthropods have the highest density in the first 5–10 cm of the soil, contributing to the plastic incorporation from the surface to the soil profile (Maaβ et al., 2017; Rillig et al., 2017; Pérez-Reverón et al., 2022; Liu et al., 2021). Due to their small size, they are involved in soil pore formation and could increase soil plastic transport (Zhu et al., 2018b; Liu et al., 2021).

The ability of soil mesofauna to transport MP particles in the soil ecosystem has been examined by studying model Collembola *F. candida, P. minuta, L. sokamensis,* and the mite *H. aculeifer* in a highly controlled experimental set-up (e.g., Maaβ et al., 2017; Zhu et al., 2018b; Kim and An, 2019; Luo et al., 2023). The total contribution of these micro-arthropods to the accumulation and movement of MP in the soil food web at different interspecific trophic levels has been suggested that can also pose another soil biota to MP particles but generally changes the physical soil properties. This occurs by the movement of the MP particles to biopores of the soil causes, inhibiting the movement of collembola

Table 4
An overview of the effect of nanoplastics and microplastics on springtails.

Specie testing	Polymer type	Size	Concentration	Exposure conditions	Observed endpoints	Reference
Springtails						
F. candida	UF, PET	<100 μm and 100–200 μm	2.5 mg of the <100 μm 5 mg of the 100–200 μm fraction	Direct exposure to Petri dishes. Without substrate. 7 days.	Ability to transport and distribute MP	Maaß et al., 2017
	PVC	80–250 μm	0 and 1 gr MP kg^{-1} soil$_{dw}$	OECD artificial soil. 56 days.	Inhibition of growth and reproduction. Changes in gut microbiota and in the carbon and nitrogen elemental absorption	Zhu et al., (2018a)
	PVC	80–250 μm	5000 items per dish	Direct exposure to Petri dishes. Without substrate. 7 days.	Transport and distribution of MP up to 9 cm.	Zhu et al., (2018b)
	PE	<50–500 μm	0.5–1% w/w	Artificial soil. 28 days.	Avoidance of plastic-spiked soils. Reproduction significantly inhibited gut microbiota alteration.	Ju et al., (2019)
	PS PS + Sulfamethoxazole	2–2.9 μm	0, 1% w/w 0 and 1% w/w (PS) + 0 and 1% mg L^{-1} (Sulfamethoxazole)	90 mm × 15 mm glass Petri dish microcosms	Altered gut microbiome and. Antibiotic resistance in exposed to mixed contamination.	Xiang et al., (2019)
	PES	12 *μ*m–2.87 mm to 4–24 mm	0, 0.02, 0.06, 0.17, 0.5 and 1.5% w/w	LUFA soil type no. 2.2.28 days	There were no differences in springtail survival or reproduction	Selonen et al., (2020)
	PP (face mask)	<300 μm	1000 mg kg^{-1} dry soil	LUFA soil type no. 2.2.28 days	No adverse effects on survival, esterase activity or oxidative stress. Significative reduction on reproduction and juvenile growth.	Kwak and An (2021)
F. candida	Tire particles[a]	80–110 μm	0, 0.02, 0.06, 0.17, 0.5 and 1.5% w/w	LUFA soil type no. 2.2.28 days	Tire particles slightly decreased reproduction and survival	Selonen et al., (2021)
	PES + chlorpyrifos Tire particles[a] + chlorpyrifos	220 ± 200 μm 80–110 μm	0.05% w/w and chlorpyrifos: nominal concentrations of 0.01, 0.03, 0.11, 0.33 and 1.0 mg kg^{-1}	LUFA soil type no. 2.2.28 days	Microplastics did not affect chlorpyrifos toxicity to springtail reproduction. Tire particles significantly decreased the chlorpyrifos-induced mortality of springtails, while polyester fibers did not.	Selonen et al., (2023)
	PP + NH_4NO_3 + $CdCl_2$ + *E. coli*	<100 and 100–200 μm	50 mg	Soil (origin not indicated)	Ability to transport MP on soils, including contaminated MP with nutrients (N), contaminants (Cd) and microorganisms (*E. coli*)	Luo et al., (2023)
Lobella sokamensis (Deharveng and Weiner, 1984)	PE and PS	0.47–0.53 μm, 27–32 μm, and 250–300 μm	Several concentrations (4–1000 mg kg^{-1})	LUFA soil type no. 2.2 <1 day	Decreased locomotion.	Kim and An (2019)
Proisotoma minuta (Tullberg, 1871)	UF, PET	<100 μm and 100–200 μm	2.5 mg of the <100 μm 5 mg of the 100–200 μm fraction	Direct exposure to Petri dishes. Without substrate. 7 days.	Ability to transport and distribute MP	Maaß et al., 2017
Cryptopygus antarcticus (Willem, 1901)	PS	<100 μm		Field collection	Plastic ingestion	Bergami et al., (2020)

Polyethylene (PE), Polyester (PES), Polypropylene (PP), Polystyrene (PS), Polyvinyl chloride (PVC), Polyethylene Terephthalate (PET), Urea-formaldehyde (UF).
Polyethylene (PE), Polyester (PES), Polystyrene (PS), Polypropylene (PP); Polyethylene Terephthalate (PET), Urea-formaldehyde (UF).

[a] Tire particles (usually generic reference, but they're a mixture of synthetic rubbers including styrene-butadiene rubber (SBR), butadiene rubber (BR), and butyl rubber (IIR)) (Ding et al., 2020; Selonen et al., 2021, 2023).

species and immobilizing them in the cavities that MP particles influxes into (Maaβ et al., 2017; Zhu et al., 2018b; Kim and An, 2019; Luo et al., 2023). Although plastics in the soil can inhibit the movement of soil organisms (Kim and An, 2019), soil microarthropods can also act as plastic transporters and move them through the soil profile, both vertically to horizontally (Liu et al., 2021b; Pérez-Reverón et al., 2022; Luo et al., 2023). Maaβ et al., (2017) observed how two collembola species, such as *F. candida* and *P. minuta* could transport plastics (Urea-formaldehyde and PET, <200 μm) up to 4 cm when exposed in a Petri dish. Due to their small size, plastics bigger than >100 μm are not expected to be ingested by soil organisms. Plastics in the soil can be easily attached to the collembolans' bodies or pushed by their legs and the head. However, as nanoplastics debris (<1 μm), they can be ingested by collembolans and transferred to the food web (Bergami et al., 2020). Linked to this question, Zhu et al. (2018b) showed how collembola (*F. candida)* and mites species *H. aculeifer* and *D. exspinosus* were able to transport PVC MP (80–250 μm) up to 9 cm for *D. exspinosus and H. aculeifer*, while transport by *F. candida* was mainly observed up to 5 cm. Besides, under predatory relationships (prey-collembola *F. candida* and predator-mite *H. aculeifer*), the plastic transport can be enhanced up to 40% in terms of the number of particles compared with single species, although with less distance of dispersion than single species. In this sense, probable biomagnification processes should be studied as indicated by these prey-predatory relationships (Zhu et al., 2018b; Liu et al., 2021b). Furthermore, Luo et al. (2023) recently appointed the role of springtails as passive plastic transporters with the ability to transport MP

Table 5
An overview of the effect of nanoplastics and microplastics on mites.

Specie testing	Polymer type	Size	Concentration	Exposure conditions	Observed endpoints	Reference
Mites						
Diverse mites' species	PE (plastic bottles) PS (packing material)	<4800 >2000	0, 5, 30, 60 and 90% w/w (manure)	Field experiment. Forest/agricultural area. Microcosm experiment	Detrimental effects to the abundance of mites (>60%)	Stamatiadis and Dindal (1990)
Hypoaspis aculeifer (G.Canestrini, 1884) *Damaeus exspinosus* (Wang and Norton 1989)	PVC	80–250 μm	5000 items per dish	Direct exposure to Petri dishes	Passive transport	Zhu et al., (2018b)
Diverse mites: *Tectocepheus velatus* (Michael, 1880) *Oppiella nova* (Oudemans, 1902) *Moritzoppia unicarinata* (Paoli, 1908) *Suctobelbella* sp. *Scheloribates* sp. Nr. *Laevigatus, Minuthozetes semirufus* (Koch, 1841) *Trichoribates novus* (Sellnick, 1928), *Eupelops curtipilus* (Berlese 1916)	PP, PES	Microfibres (length 2–3 mm or 5–6 mm; diameter of fibres 22.92 ± 0.17 μm for PE and 33.33 ± 0.07 μm for PP fibres)	0.4% w/w	MP addition to microcosm experiment (550 ml volume)	Oribatid species richness was not affected by MP addition. No effects on reproduction (new juveniles)	Barreto et al., (2020)
O. nitens	PES	12 μm–2.87 mm to 4–24 mm	0.5 w/w	LUFA soil type no. 2.2.28 days	There were no differences in survival and reproduction.	Selonen et al., (2020)

Polyethylene (PE), Polyester (PES), Polypropylene (PP), and Polyvinyl chloride (PVC).

on soils, including contaminated MP with nutrients (N), contaminants (Cd) and microorganisms (*E. coli*). These observations could have a beneficial or adverse impact on ecosystems since nutrients and contaminants could be transferred through springtail activities, could spread the soil system and, therefore, diffuse contamination.

Regarding soil microfauna organisms, Fueser et al. (2019) showed how different nematode species (*C. elegans*, *P. thienemanni*; *P. acuminatus*; *P. regenfussi* and *A. nanus* can ingest and transfer to food-chain different polystyrene beads (up to 6 μm size), although the plastic uptake is highly dependent on nematode diet. In this sense, studies to assess the plastic movement by soil fauna are scarce. As highlighted, micro- and mesofauna can play an essential role in the plastic movement in the soil system, especially on macropores and coarse soils (Bläsing and Amelung, 2018). However, the movement and transport of plastic items in soils are highly dependent on soil biodiversity and the food web (Chae and An, 2018; Okoffo et al., 2021), as shown by the study carried out by (Zhu et al., 2018b), and this kind of studies should take into account these specificities.

4.2. *Can soil micro- and mesofauna increase plastic biodegradations?*

Besides their role in MP transport, the fauna activity on plastics can also increase the (bio)degradation processes (Ali et al., 2021). Soil macrofauna can increase physical fragmentation through ingestion, digestion and egestion processes, as reported for earthworms (e.g., Huerta Lwanga et al., 2017a,b, 2022; Sánchez-Hernández et al., 2020; Wang et al., 2022d), land snails (Song et al., 2020), terrestrial isopods (Wood and Zimmer, 2014; Helmberger and Grieshop, 2022) or different insect species (e.g., Ali et al., 2017, 2021; Peng et al., 2020; Immerschitt and Martens, 2021; Jiang et al., 2021; Sánchez-Hernández, 2021; Fudlosid et al., 2022; Helmberger et al., 2022; Palmer et al., 2022) for PE, PS and EPS, PVC or PLA. Through ingestion or biotic interaction with the MP movement in the soil, plastic debris can interact with gut microbiotas being these items more palatable by micro- and mesofauna (e.g., Sánchez-Hernández, 2021; So et al., 2022) as indicated by Galloway et al. (2017) for marine debris. Other termite studies showed they could gnaw or make cuts and scratches on polyethylene and polyamides (Leonov and Tiunov, 2020). However, studies with micro- and mesofauna are scarce due to their small size limiting MP uptake and biodegrading them. Zhang et al. (2022b) reported a potential PS biodegradation due to protist activity. Still, studies with nanoplastics, micro-, and mesofauna are needed to understand if these organisms can also uptake and biodegrade these plastics, as nanoplastics, through ingestion. As the previous sections show, plastic uptake can modify the gut microbiota and reduce diversity. However, it's highly recommended to increase the research on how enchytraeids, springtails or mites could uptake, digest and potentially degrade some microfibres and small-size particles (Ali et al., 2021).

5. Concluding remarks and future prospects

The impacts of MP on micro- and mesofauna showed similar issues to those reported for macrofauna, with some impacts on the avoidance of contaminated soils, reproduction, oxidative stress or changes at the gut microbiota level. The fact that many of these organisms cannot eat the MP due to their size also reduces the potential toxicity of the MP. However, due to the degradation of plastics by abiotic and biotic means through the microbial community or macrofauna (e.g., earthworms or insect larvae), they will become smaller and, therefore, more susceptible to ingestion by micro and mesofauna, and through biomagnification processes. Besides, the impact of nanoplastics seems toxic to these organisms, as reported for nematodes, but more studies with nanoplastics are also needed. Despite the fact that these organisms cannot eat several plastic items when agrochemicals contaminate them, these will pose a risk for micro and macrofauna organisms.

In this sense, ecotoxicological tests about the impact of MP on terrestrial organisms should consider holistic approaches with different levels of biological organization and soil fauna, especially using multiple different levels of soil fauna and species mixed plastic contamination rather than single species or single contamination. In this sense, studies with mixed contaminations or community composition and diversity are scarce. Only some soil organisms, such as earthworms or nematodes, have been studied in detail when collembola has a crucial role in particle transfer through the soil profile, or protists may introduce MP into the soil food web. A similar question can be highlighted for biodegradable plastics since most of the research has been focused on non-biodegradable plastics, when the use of these new polymers is increased due to regulation on single-use plastics.

Multi-scale and multi-generational studies are needed to reveal the real impact of plastics on soil organisms. However, ecotoxicological studies also require standardization on methodologies and protocols, exposure times or realistic concentrations. A similar question can be indicated to public and open databases for microplastic identification. Also, international laboratory intercomparison analyses are needed to assess the consistency and quality of results.

In addition, more research should focus on the potential role of micro- and mesofauna as transporters through the soil profile and their potential role as plastic degraders. Finally, more research should be focused on the interactions between soil contaminants and MP and the potential role of MP as contaminant carriers, both added during manufacturing as additives or adsorbed from the environment, such as inorganic or organic contaminants in agricultural areas.

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E.D.: Conceptualization, methodology, formal analysis, investigation, writing – original draft, supervision; **T.S., W.C. and J.Y.L.:** Conceptualization, methodology, formal analysis, investigation, writing and reviewing – original draft; **J.S.:** investigation, writing and reviewing – original draft; **A.R.S:** Conceptualization, methodology, formal analysis, investigation, writing and reviewing – original draft, supervision.

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.

Data availability

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

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