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Recent trends and open questions regarding the effects of microplastics on soil, plants and soil microorganisms

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Abstract

In recent years, microplastics have been extensively detected in sea, freshwater, soils and organisms. The microplastics pollution is of increasing concerns for soil health. Microplastics are considered as an emerging threat to the agroecosystems, where soils may represent a reservoir for plastics pollution. Microplastics in soils could alter soil properties, plant growth, soil invertebrate, abundance and activity of soil microorganisms. Further investigations are needed to evaluate the overall effect of microplastics on soil ecosystems services.

Key words: microplastics, pollution, soil, plants, soil microorganisms

Introduction

Pollution by plastic waste is one of the planet's most serious environmental problems. Research still identifies the magnitude, effects and damage of this pollution (Mitova et al., 2019). More than 10 years ago, the problem of microplastics (MP) presence in various ecological spheres has become a global concern. Initially, studies in this field focused on the presence and potential negative effects of MP in the marine environment (Thompson et al., 2004). Thus, from 2009 to 2019, the number of works mentioning the term "microplastics" published in the Scopus database grew from 2 to 939 (Petersen & Hubbart, 2021). Research on microplastics in soil can be traced back to 2012 (Rillig, 2012). Since then, the relevance of studying this problem has become obvious to more and more researchers. According to data obtained from the Web of science database using Citespace software (Ya-di et al., 2022), the number of articles on microplastics in soil increased slowly between

2016 and 2018. Then, from 2018 to 2021, there has been an exponential increase in the number of publications on this topic.

According to the commonly used gradation in many studies, MP are defined as plastic particles of size less than 5 mm (GESAMP, 2016). It is worth noting that this definition has been relatively well-established since 2009 (Arthur et al., 2009). The definition given by the joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) also includes the nano-sized particles in the MP categorization (GESAMP, 2016). At the same time, researchers often distinguish the term "nanoplastic", the definition of which is less universally agreed upon. Some researchers define the upper threshold of nanoplastic particle size as 100 nm (Gigault et al., 2018). The key point for prospective unification of terminology here might be, first of all, the size of regarded particles from 1 nm up to 1 μm. It is also suggested that in order to distinguish the term "nanoplastic", not only the size of the particles but also their properties, in particular their colloidal behavior, should be taken into account (Gigault et al., 2018; Gigault et al., 2021).

Taking into account that there are still some ambiguities in the use of the definitions of "microplastics" and "nanoplastics", the efforts of scientists and organizations to further unify and standardize the terminology in this field of research seem to be promising. The same also applies to the development and improvement of methods for identification and quantification of MP content in soil.

Pathways of MP inputs to soil and plastic production

At present, a general understanding of the main pathways of MP input into the soil has been formed. Microplastics can enter the soil not only as a waste degradation product (Rillig, 2012) and from sewage sludge when it is used as a fertilizer (Corradini et al., 2019), but also from landfill leakage, urban-rainfall runoff, atmospheric deposition (Blasing & Amelung, 2018; Tian et al., 2022).

Another notable source of microplastics in the soil is the plastic mulching. This widespread practice involves the use of plastic film, thereby increasing water use efficiency, provides weed and soil temperature control and other benefits. These measures lead to higher yields of cultivated plants. However, a significant amount of mulch residue has been produced by the widespread usage of this technology (Liu et al., 2014). These mulch residues, by degrading, cause accumulation of microplastics in cultivated soils (Petersen & Hubbart, 2021). In this regard, it is important to note the following trend. The largest number of publications of microplastics in soil between 2016 and 2021 originated from China. Not only concerns about soil quality and human health are stated as reasons for this, but also because China has the largest number of agricultural lands where plastic film mulching is used (Ya-di et al., 2022). Furthermore, China produces the largest amount of plastic. For example, China accounted for 32% of global plastic production in 2021 and 2022, up from 29% in 2017. At the same time, plastic imports from China to the European Union increased from 8.7% to 11.8% in 2022 compared to 2021 (PlasticsEurope AISBL, 2022; PlasticsEurope AISBL, 2023).

There has been an increase in the amount of plastic produced in recent years. The global plastic production amounted to 370.5, 379.8, 380.4, 394, and 400.3 Mt in 2018, 2019, 2020, 2021, and 2022, correspondingly. The European plastic production shows a less clear-cut trend: 62.3, 60.2, 57.7, 60.8, and 58.7 Mt in 2018, 2019, 2020, 2021, and 2022 (PlasticsEurope AISBL, 2023).

The European plastic data shows that in 2021 the European polypropylene (PP) production amounted to 16.6%; low density polyethylene (PE-LD) and linear low density polyethylene (PE-LLD) - 14.7% of all the types of plastic produced. The highest contributions to the global plastic production for 2021 have PP (19.3%) and PE-LD + PE-LLD (14.4%) (PlasticsEurope AISBL, 2022). The same two types of plastic retained their top-2 position in global and European production in 2022. European PP production amounted to 15.4% and PE-LD + PE-LLD production to 13.4%; and global production – 18.9% PP and 14.1% PE-LD + PE-LLD (PlasticsEurope AISBL, 2023). Taking this into account, when selecting the type of MP, further studies can be guided by data on the production of a particular type of plastic. Pollution research requires an understanding of its quantitative content in the medium being studied. Compared to the studies of MP in water, yet there is no generally accepted method for MP detection in soil. Soil is a complex system and MP can interact with its components (Miao et al., 2023). Therefore, the overall process of MP detection in soil is a complex process and consists of several steps: representative sampling, extraction, purification, identification and quantification. For each of these steps, different methods and approaches are currently practiced, many of which require consideration of not just the properties of the soil being investigated, but also the type of MP and their particle size (Braun et al., 2018; Dorau et al., 2023; Miao et al., 2023; Mushtak et al., 2024). Given the above-mentioned challenges of MP detection in soil, model experiments are of particular importance. In specific cases where the main source of MP input to the soil is known, e.g., when using plastic film for mulching, the choice of MP type for model experiments will be appropriately justified by the particular problem being studied. Such approach looks promising for obtaining practical recommendations for agricultural management, as well as for assessing the anthropogenic impact of industrial activities on soil.

The possibility of microplastics migration from soil to other media (including plants) has been proven. This can eventually pose a risk to human health as well. It was found that microplastics can enter the human body through the trophic chains (Zhao et al., 2024). This indicates that the problem of microplastics in the soil should be taken into account in agricultural management. Despite the development of the topic of microplastics in soil, complex studies of its effects on soil properties, soil microorganisms and plants are not common. Further integrated assessments of the effects of microplastics on soil properties, plants and soil microorganisms will make it possible to create a more comprehensive overview of the processes associated with microplastics in soil under natural conditions.

Effects of microplastics on soil properties

The impacts of MP on soil physicochemical properties is a complex matter, and the results of studies often vary widely depending on the soil being investigated and the type, size, and concentration of MP. This could be observed from the results of the studies that determined parameters such as pH (Boots et al., 2019; Qi et al., 2020 a; Qi et al., 2020 b; Wang et al., 2021); soil aggregate properties (Fang et al., 2024), and in particular, the stability of soil aggregates (De Souza Machado et al., 2018; Zhang et al., 2019). As in other studies of MP in terrestrial ecosystems, this area mainly lacks a standardized approach to selecting the type, size, shape, and concentration of MP particles used in model experiments. However, for soil bulk density, some general trends of MP impact on them can be distinguished. A decrease in soil bulk density was observed under the influence of polyester fibers applied to the soil in amounts up to 0.4% w/w (De Souza Machado et al., 2018; Lozano & Rillig, 2020) and in the amount of 1% w/w (Guo et al., 2021); low-density polyethylene particles (LDPE) in amounts of 0.5%, 1% and 2% w/w (Qi et al., 2020 a). Apparently, fibrous MP particles influence the soil structure in a special way due to the possibility of entangling soil aggregates, which is of particular interest for further research in this direction. The addition (10%) of the microplastics (Polycarbonate (PC), Polymethyl methacrylate (PMMA)) in Vertic Phaeozem and Haplic Cambisol in the laboratory experiment decreased the water retention capacity throughout the whole range of water suctions (Doneva et al., 2023). The reduction effect on soil thermal properties of PMMA was more pronounced than of PC for Vertic Phaeozem. The addition of PC almost did not influence the volumetric heat capacity in both soils. The decrease of thermal conductivity and thermal diffusivity was better pronounced in the studied Haplic Cambisol (Doneva et al., 2023).

Effects of microplastics on plants

There are evidences of microplastics affecting plant growth and development. For example, PP, polyethylene terephthalate (PET) and high-density polyethylene (HDPE) decreased root biomass and average root diameter while increasing total root area and root-leaf biomass ratio (De Souza Machado et al., 2019). There are distinguished both direct impacts of microplastics on plants, when MP directly change physiological processes in plants, and indirect, which are a more complex pattern. Indirect effects are associated with changes in soil properties, structure of plant communities, combined toxic effects with organic pollutants and/or heavy metals, changes in soil microbiota and fauna (Iqbal et al., 2023). Among other factors, changes in the structure of plant communities can occur due to allelopathic interactions between plants (Lozano & Rillig, 2020). This poses a potential risk to biodiversity. These effects depend not only on the type of plastic, but also on its amount in the soil and the size and shape of its particles. At the same time, the negative impact of microplastics on plant growth and development is generally noted (Jia et al., 2023).

Some studies have shown that there is a possibility of nanoplastic particles entering plants. For example, polystyrene particles with a size of 100 nm entered the roots of *Vicia faba* (broad bean) seedlings together with water, showing a noticeable phytotoxic effect at a concentration of 100 mg/L (Jiang et al., 2019). Using laser confocal scanning microscopy (LCSM), these particles were detected in plant root tissues. The researchers suggested that nanoplastic particles, once inside the roots, could block intercellular nutrient transport. Meanwhile, larger size microplastic particles (5 µm) were not detected in plant root tissues in an amount as high compared to the smaller size particles. In general, it was observed that 100 nm polystyrene particles had greater toxic effect on *V. faba* plants than 5 µm particles.

Particularly noteworthy is the possibility of combined effects of MP and heavy metals (HM) on plants. This problem is of particular concern given the ability of HM to accumulate in plants and adversely affect human health. In this context, consideration must be given to more than just how MP may alter the availability of HM to plants (Wang et al., 2021). Considering the ability of nanoplastic particles to enter the roots of plants, the question arises about their ability to transfer HM. It is outlined that at present the processes of HM entering together with MP and nanoplastic particles into plant tissues are insufficiently studied (Wu et al., 2024).

Effects of microplastics on soil microorganisms

The soil microorganisms play many fundamental roles in delivering key ecosystems services that are responsible for important functions like releasing nutrients, soil organic matter decomposition, forming soil structure. Additionally, the rhizosphere of plant roots contains distinct microbial populations, and crop development and yield could depend on these interactions. As with plants, microplastics can affect soil microorganisms either directly or indirectly (through changes in soil properties). The full picture of the effects of microplastics on microbial communities in the soil (where plants also grow) remains to be elucidated.

Substrate-induced and basal respiration of soil microorganisms, soil microbial biomass carbon and microbial metabolic coefficient are integral and sensitive indicators representing the state of the microbial community in a particular soil plot. The state of the soil microbiota could be important for identification the initial stages of soil degradation, so further research in the area of representative indicators of the state of the microbial communities in microplastics-polluted soils will help to identify critical concentrations of microplastics in soil.

Thus, by determining these parameters together with soil enzyme activity, it was found that polystyrene nanoparticles (PS-NPs) led to a significant decrease in the biomass of soil microorganisms and soil enzyme activity. This trend was generally evident with the increase in the amount of nanoplastic (100 and 1000 ng PS-NPs g^{-1} dry soil). Meanwhile, basal respiration and metabolic quotient increased with increasing amounts of nanoplastic over time, which may be explained by the use of available residues of lysed cells by surviving bacteria. Researchers highlight the antimicrobial effect of PS-NPs (Awet et al., 2018). Considering the most likely selective effect of microplastics on soil microorganisms, it seems necessary to conduct microbial culture tests of soils with microplastics. At the same time, it was found that the addition of microplastics particles (polypropylene, 7% w/w and 28% w/w, particle size less than 180 μm) resulted in the stimulation of fluorescein diacetate hydrolase (FDAse) in soil (Liu et al., 2017).

Changes in soil microbial communities under the influence of MP are also confirmed by gene sequencing. This was shown in an experiment with polypropylene (PP) (4 mm particles) and expanded polystyrene (ePS) (1-3 mm particles). Both MP were applied to the soil at an amount of 0.5% w/w. The results showed that the composition of bacterial communities differed between the main soil to which MP was applied and the control without MP. MP application increased the diversity of microbial communities compared to the control variant. Significant differences were also found between the composition of bacterial communities found on MP particles and those found in the main soil. This makes it possible to conclude that MP particles provide a new ecological niche for soil microbes (Kublik et al., 2022).

Conclusion

Taking into account that there are still some ambiguities in the use of the definitions of "microplastics" and "nanoplastics", the efforts of scientists and organizations to further unify and standardize the terminology in this field of research seem to be promising. The same also applies to the development and improvement of methods for identification and quantification of MP content in soil.

Many research results and reviews show that MP particles in soil can often have multidirectional effects on soil properties, plants, and soil microbiota. Evidently, the use in further studies of an integrated approach to assess the impact of MP on soil services and soil health will provide a comprehensive picture of the behavior of this relatively new pollutant in terrestrial ecosystems. In future it will be a big challenge for scientists to explore and evaluate all effect of microplastics to the environment and to elaborate methods and techniques for remediation.

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