

NETmicroplastic in agricultural soil and its impact on soil properties

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Abstract

Implementing “soil health” means sustainable management of agricultural soils, avoiding toxicities, and sensible use of resources to minimize waste. In this context, the use of plastic in agriculture in form of plastic products, the application of polymers and additives in fertilizers, and plastic input through littering and tyre wear demands our special attention. Uncertainty and open questions relating to effects of plastic and its degradation products such as microplastic (MP) on the soil environment, the soil biota, and human health partly result from the lack of robust and standardized detection and measurement methods. Also, environmental, economic, and societal problems around MPs in soil cannot be adequately addressed due to lack of coordination among the various relevant players and initiatives in research and policy. NETmicroplastic (www.net-microplastic.eu) responds to the need of connecting among a fragmented research & innovation and policy landscape by creating a community-supported environment. The network fosters provision of solid data for science-based impact assessment of MP in soil together with much-needed technological innovations, including biodegradable alternatives to conventional plastic. Here, we reflect upon a number of action fields that are key to the NETmicroplastic initiative from small to large-scale perspectives. In addition, we portray the overall awareness situation around MP in soil.

KEYWORDS

agricultural soil, biodegradable plastic, compost, microplastic, soil communities

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1 | INTRODUCTION

The trend in soil health is to bring a large part of agricultural soil into sustainable soil management to reduce loss of soil mass and structure, to avoid the emergence of toxicities due to enhanced exposure to chemical pesticides and to improve the use of resources to minimize waste. The use of plastic in agriculture in the form of

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plastic products like foils, nets, clips, and so forth, compost products, polymers and additives in fertilizers, irrigation water, littering and tyre wear plays a critical role in this context (Figure 1).

Several authors (Chia et al., 2022; Hofmann et al., 2023; Iqbal et al., 2023; Liwarska-Bizukojc, 2021; Pérez-Reverón et al., 2022) have critically reviewed the impacts of microplastic (MP) on physico-chemical soil properties, soil ecology and agricultural production. Due to its small particle size, large specific surface area, and strong hydrophobicity, MP can adsorb to other soil pollutants (e.g., pesticides, antibiotics, plasticizers) and microorganisms. MP is reported to affect soil properties depending mainly on soil type and MP characteristics. It is taken up by soil animals via feeding pathways, and over time is prone to forming nanoplastic that migrates and accumulates in plants, thereby entering the food chain and potentially causing harm to humans. Presently, information is limited about MP as influencing factor of soil physical properties such as water holding capacity and soil processes like aggregation, besides its potential impact on the performance and composition of soil microbial communities and soil fauna and

Highlights

- NETmicroplastic is a sustainable RTI partnership of ten partners from Austria, Germany, Spain and the Netherlands dedicated to microplastic (MP) in agricultural soils.
- NETmicroplastic aims to combine impact assessment of MP in soils with the development of biodegradable plastics as a possible technological solution.
- The potential impact of MP on soil organisms and biodiversity is discussed.
- The importance of education and awareness-raising to reduce plastic use is highlighted.

flora. Even less is known about the migration, degradation and mode of degradation of MP in soil.

An important reason for the many open research questions is the lack of a robust standardized detection method that allows to analyse MP in soil in a time-efficient manner



FIGURE 1 Schematic overview of the use of plastic products in the environment and their potential impact on agricultural soils.

and compare within different analysis labs. In fact, data can hardly be compared due to different soil sampling, different sample preparation and analysis methods. Most studies focus on larger MP particles (>1 mm) using microscopic techniques in combination with intense sieving of the soil sample, while detection of smaller fractions, which are more abundant in soil, requires micro-Fourier-transform infrared (μ FTIR) (down to 20 μ m size) or Raman spectroscopy (down to 1 μ m) or (for nanoplastic particles) X-ray photoelectron spectroscopy or pyrolysis coupled with gas chromatography–mass spectrometry (Pyr-GC–MS) or thermal extraction desorption-GC /MS (TED-GC/MS) (Huerta Lwanga et al., 2022; Ivleva, 2021; Li et al., 2020; Pérez-Reverón et al., 2022, 2023; Wang et al., 2023). Thermoanalytical methods appear to be most promising not only for the detection of nanoplastics, but also for the detection of microbioplastics, for which, in contrast to conventional MPs, appropriate detection methods are lacking completely (Fojt et al., 2020) and which are generally much less studied. Detection technology is progressing rapidly thanks to automated quantification and the use of spectral libraries and toxicity databases and the implementation of machine learning approaches and powerful artificial intelligence (AI) algorithms (Hufnagl et al., 2022; Zhang, Zhang, & Zhang, 2023).

However, knowing the type of plastic polymer and the concentration is not enough to understand the consequences of the measured MP. Since the properties, size, shape, associated substances, and so forth of MPs are highly variable and MP composition may differ considerably, the same type and concentration of MP particles can result in completely different ecological and toxicological profiles and thus risks. Indeed, it has been shown that nominally identical materials, such as polystyrene particles, can interact differently with cells if their surface charge is different (Wieland et al., 2024). Therefore, Li et al. (2024) proposed a new concept, a more holistic approach called “microplastome”, which is defined as “the entirety of various plastic particles (<5 mm), and their associated matters such as chemicals and microbes, found within a sample, and its overall environmental and toxicological impacts”. This collective quantification and characterization of MPs should contribute to a better reflection of the real-world impact of MPs and, presumably, to more effective pollution management.

Most data available consider MP in arable lands and mulch foils as the main source, NETmicroplastic sets a focus on vineyards and orchards, and on compost as a carrier for MP and input pathway of soil. Comprehensive studies in this context have been initiated in several European countries to estimate the extent of MP pollution, for example, the Plasbo project

in Austria and iMulch in Germany. In NETmicroplastic, we will not focus on MP analysis methods or the harmonization of sampling procedures, sample preparation or analysis techniques., In NETmicroplastic (www.net-microplastic.eu) stakeholders from Austria, Germany, Spain and the Netherlands are creating a community-supported environment that aims to provide solid data for science-based impact assessment of MP in soil and technological innovations including biodegradable alternatives to conventional plastic. NETmicroplastic consists of nine core network partners (five national, four European) representing all relevant stakeholder groups, with AIT Austrian Institute of Technology as the lead partner. Three thematic groups, technology, environment, and education help to remove barriers and will link the different impact fields in interdisciplinary teamwork and transdisciplinary collaboration, expanding from local to national and European level.

In the following, a number of action fields that are key to the NETmicroplastic initiative are reflected upon from small to large-scale perspectives.

2 | MICROPLASTIC IN SOIL IN THE EU-WIDE AND INTERNATIONAL POLICY CONTEXT

NETmicroplastic connects to the EU-wide and international discourse by seeking dialogue with related initiatives and linking with stakeholders and key players in society at multiple levels of organization. Notably, several major EU policy strategies such as the European Green Deal, the Circular Economy Action Plan and the European Strategy for Plastics in a Circular Economy emphasize on the need to reduce plastic use and waste. The EU Action Plan ‘Towards Zero Pollution for Air, Water and Soil’ demands that by 2030 the EU reduces MPs by 30%. There is also other European legislation concerning the use of plastic components, such as the EU Fertilizing Products Regulation, which is demanding to eliminate non-biodegradable polymers and additives from fertilizers by 2025. According to the Austrian bioeconomy plan, raw materials that cannot be reused through the circular economy must—as far as possible—be replaced by renewable raw materials. In Austria, the National Action Plan on MPs 2022–2025 identifies areas for action such as strengthening the data situation and raising awareness. NETmicroplastic contributes to these fields focusing on research & innovation (R&I) and awareness-raising and schools to support the transition to a sustainable agriculture. Besides identifying and mapping MP activities in a regional,

national and European context we elucidate the current state of knowledge and awareness regarding MP in agricultural soil among multiple stakeholder groups. The collected data will provide a basis to fill transitional gaps for a MP strategy and future national and European strategic R&I agendas.

NETmicroplastic takes account of past and ongoing research projects in the field of impact assessment and technology innovations through compiling relevant Austrian and European projects, strategies & policies (government-driven efforts), and initiatives (public-driven) in a public database [Database-NETMP\(net-microplastic.eu\)](https://netmicroplastic.eu) that is open to continuous extension. Using a stringent search strategy, only projects addressing MP in soil systems and/or relevant analytical methods were included in the database.

In addition, the network collects views by industry, policy, and the farming and educational sectors, as they are considered essential for portraying the overall situation around MP in soil. Outcomes from a wide range of public consultations and results from surveys carried out on the topic in various contexts are discussed in the following chapter.

3 | AWARENESS, KNOWLEDGE AND PERCEPTION OF MICROPLASTICS IN SOIL

Information sharing, education and awareness-raising are key to reducing plastic use wherever possible and appropriate, and to identifying easy-to-implement sustainable solutions. This will require the involvement of all relevant stakeholders, from industry to farmers, from the general public to the education sector, and elucidation of their respective perceptions and behavioural patterns. There are multiple reports stating that a majority of people have heard about MPs, however, mostly in the context of aquatic environments (Cammalleri et al., 2020; Dowarah et al., 2022; King et al., 2023; Kramm et al., 2022).

Several articles highlight the prominent role of the media in raising awareness and knowledge about MPs, with the internet and television often ranked as the main sources of information (Cammalleri et al., 2020; Raab & Bogner, 2021). Media have the potential to shape public understanding and conceptions through the way of topic presentation, by exaggeration, oversimplification, repetitive reporting, images (Henderson & Green, 2020) or media narratives (Kramm et al., 2022). For example, the narrative “microplastics in soil limit the growth of plants” was known by 66% (often and rarely heard), while “microplastics in the sea threaten fish stocks” was known to almost all respondents (98%) (Kramm et al., 2022). Janoušková et al. (2020) showed that the media was the main source of

information for questions about the source (93%), formation (55%), and occurrence of MPs (30%). Two-thirds of the respondents expressed the preconception that MPs occur only in water or in water biota reflecting the information provided by media. This result is similar to a Norwegian free-association survey where relatively few people considered plants and land/soil as places where MPs can be found (Felipe-Rodriguez et al., 2022).

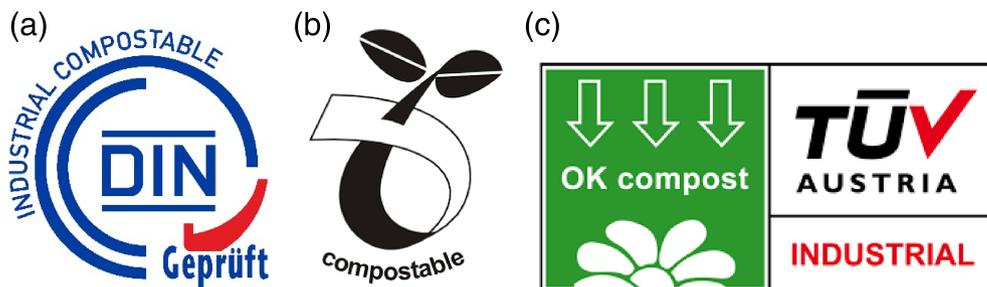
Europeans' attitudes towards MPs are very similar: Almost 9 in 10 (88%) agree that they are worried about the environmental impact of MPs, including half (50%) who “totally agree”, while just 9% disagree (European Commission, 2020).

In a Norwegian free-association survey, “consequences of microplastics” was mentioned as the first thing that came to mind when people (51.9%) read or heard the word “microplastics” (Felipe-Rodriguez et al., 2022). According to a German consumer monitor, MPs top the list of concerns (66% are very concerned, 20% are “moderately” concerned), ahead of antibiotic resistance (58%/20%) and pesticide residues in food (57%/19%). Regardless of geographic differences, concern about MP pollution is high across all populations, but rarely associated with soil or agriculture. This may be because, until recently, soil has only been recognized for production, not as a critical source that needs to be protected, and the link between healthy soil, clean water, and habitats for biodiversity has not been established. Increasing emotional and distance-related alienation from nature and lack of information about the many roles of healthy soil and how food is produced from plants may contribute to the low perception of soil as an important resource to be protected. More information about the importance of healthy soil is needed to engage people and shape their perceptions and behaviours, and ultimately the treatment of soil, reducing the use of plastic materials and littering.

Littering is estimated to be the largest source of MPs in agriculture, ahead of various amendments (sewage sludge, compost, fertilizer) and mulch films (Bertling et al., 2018; Kalberer et al., 2019).

In Europe, half of the produced sewage sludge produced by wastewater treatment plants is spread on agricultural fields as a fertilizer, rich in nutrients especially nitrogen and phosphorus (Radford, 2022). However, sewage sludge contains high levels of MPs in addition to other potentially hazardous substances. For this reason, sewage sludge was banned in the Netherlands in 1995 and in Switzerland in 2006. When it comes to MPs, we need to identify the main sources of these substances in society and not just focus on possible sources such as sewage sludge, because “the content of sewage sludge is a reflection of society and its choices” say Swedish stakeholders regarding the resources and risks of sewage sludge application to agricultural land (Ekane et al., 2021).

FIGURE 2 Certification logos for industrial compostable products: (a) DIN CERTCO, (b) Seedling logo and (c) TÜV Austria logo, all of them based on EN 13432.



MPs in compost are also problematic. 13% of farmers who used compost in the past have stopped using it for this very reason despite expected benefits such as increased humus content and soil revitalisation but would use compost again if it were of a higher quality and more readily available (Lampert & Lippl, 2023). A regional map of composting facilities, together with information on the quality of compost including levels of contamination and its distribution through these channels, would be helpful.

Compost contamination is a result of how (collection system) and where (rural vs. urban) biowaste is collected. Many people throw biowaste into the trash along with the plastic bag used to collect it, both conventional plastic bags and plastic bags labelled as biodegradable, compostable, or bio-based. There is little knowledge about the different properties and composition of the pre-collection aids, such as the possible addition of mineral oil-based plastics to “biodegradable bags” (Pamperl et al., 2022). Awareness of the individual logos and knowledge of their meaning was also very low (Pamperl et al., 2022). Figure 2 shows three certification logos for compostable plastic products according to the European standard EN 13432. EN 13432 defines the minimum requirements to be met for industrial composting, such as disintegration after 12 weeks and complete biodegradation after six months (at 58°C). For the vast majority of composting facilities, compostable and degradable plastic is a disturbing substance that is usually separated prior to the composting process, resulting in increased costs (Ergebnisbericht_Kompostierumfrage.indd(duh.de), accessed on 12.1.2024). Moreover, even plastics labelled as biodegradable are often still found after the composting process. This was demonstrated in a public composting experiment in 2022 for different plastic collection aids (<https://www.duh.de/bioplastik/>). Recently, it was reported that microbioplastics could be found in certified high-quality compost produced in eight different composting plants in Germany (Steiner et al., 2024).

Discussions on the plastic challenge in the composting process have revealed the necessity for a clear and uniform labeling scheme for carrier bags. Such a scheme would facilitate the detection of plastic waste with an AI scanner

system built into garbage trucks. Furthermore, there is a need for better adaptation of polymer and environmental factors, such as the plant operating conditions that control the biodegradation process (Sander et al., 2024), to enable faster degradation of bioplastic products.

The use of bioplastics, preferably biodegradable for agricultural tools and equipment, is one of the proposed technological solutions that, despite some technical hurdles, might contribute to a valuable reduction of persistent plastic in soil. A survey with 384 participants from 42 countries (Filho et al., 2022) revealed that the majority of respondents anticipate a promising future for bioplastics. Specifically, 95.1% of respondents indicated that they believe bioplastics can fully or partially replace conventional plastics.

What do farmers who would need to adopt the new technological solutions think about bioplastics, what do they know about them and are they willing to test alternative biodegradable products to reduce the amount of plastic unintentionally added to the soil? According to recent survey data, farmers are open to testing alternative plastic materials, provided that the technology in question has specific characteristics (Yang et al., 2023) and affordable alternatives are available (King et al., 2023). What strategies can be employed to better engage farmers and keep them informed of new trends? Information, education, and training are considered essential for building confidence and investment in biodegradable plastic products (Yang et al., 2023).

4 | IMPACT OF MICROPLASTIC ON SOIL ORGANISMS AND BIODIVERSITY

Following entrance into the soil via the pathways given in the introductory section, MPs may continue to migrate through the soil system. MP migration may be accelerated by biotic and abiotic processes, potentially expanding the pollution range (Zhao et al., 2022). Thus, soil organisms actively modulate MP fate in soil and at the same time are affected by MP in their biological and ecological functions.

It has been well documented (e.g., Kublik et al., 2022) that the residing soil microorganisms readily colonize introduced MP materials, which thus form a new habitat for microbial assemblages. The so-called “plastisphere” is characterized by distinct microbial communities. Kublik et al. (2022) identified certain bacterial phyla that were enriched on MP materials and considered them as core microbiome of the plastisphere, which included Actinobacteria, Proteobacteria and Patescibacteria. Among MP colonizers, specific strains have been retrieved that are able to degrade plastics. Notably, the Actinobacteria phylum has been found enriched on the surfaces of polyethylene (PE) (Huang et al., 2019; Wang et al., 2020; Yi et al., 2020), whose members are known to produce extracellular polymers such as dextran, glycogen, levan, and *N*-acetylglucosamine-rich slime polysaccharides, facilitating their attachment to plastic surfaces for subsequent microbial action (Amobonye et al., 2021).

Effects of MPs on the soil biota (i.e., microbiota and fauna) was investigated in a recent meta-analysis (Liu et al., 2023) based on 781 observations from 92 publications, showing that MPs significantly increased soil microbial biomass, while growth and reproduction of soil fauna (nematodes, springtails and earthworms) were reduced. Results indicated that MPs significantly decreased soil bacterial diversity and shifted microbial community structure, and that the effect of MPs on soil bacteria was more intense than that on soil fungi. Most studies, however, used laboratory experiments not fully reflecting complex field situations. In Yan et al. (2021), the authors substantiated that polyvinyl chloride (PVC) MP pollution at environmentally relevant concentrations did not have a significant effect on overall bacterial community diversity and composition in soil over the course of 35 days, although a number of bacterial genera were significantly reduced or enriched.

It has been postulated that MP impacts on the soil (micro)biota largely through alterations in habitat space and conditions, which are important factors, in particular, for mycorrhizal fungi. Here, plastic fibres modify the soil structure and alter soil aggregate stability with potential consequences for mycorrhizal fungi and their roles in soil aggregation and water and nutrient transport (Leifheit et al., 2021). Indeed, soil experiments using different particle sizes showed that existence of PE-MPs significantly altered soil physicochemical properties, inhibited soil enzyme activities, and changed the richness and diversity of bacterial and fungal communities in dependence of aggregate properties (Hou et al., 2021). Considering MPs with different characteristics, the various polymer types caused distinct effects on soil bacterial communities, presumably due to their different polymer backbones of chemicals. In comparison with particles, MP fibres and films caused greater shifts in community composition, probably

due to stronger disruptive effects to the natural soil structure (Sun, Duan, Cao, Ding, et al., 2022).

Similarly, distinct effects were reported from conventional versus biodegradable MPs on the soil microbial community, functionality, and metabolome. Treatment with biodegradable MPs significantly changed soil microbial communities, which compared with conventional MP treatments showed a higher potential for carbohydrate and amino acid uptake (Sun, Duan, Cao, Li, et al., 2022). While stronger impacts from biodegradable versus conventional MPs were reported on the soil microbial community, there appeared to be weaker negative impacts on the soil fauna (Liu et al., 2023). Likewise, smaller size-MPs appeared to have more adverse effects on soil bacterial diversity and the growth and reproduction of nematodes, but this trend was the opposite in the reproduction of earthworms (Liu et al., 2023).

MP particles in soil frequently are in the range of few micrometres only, and due to their small size can be ingested by the soil biota and thus may accumulate along the food chain. Among the first studies of this type, Huerta Lwanga et al. (2017) and Rillig et al. (2017) have provided evidence that PE MP particles are taken up by anecic earthworms and can clearly be transported relatively quickly downward from the soil surface to a depth of 10 cm, potentially entraining wider ecotoxicological consequences. However, drawing conclusions from studies on the ecotoxicological effects of MP on soil biota is hindered by differences in experimental methods and the concentration, type, shape and colour of the tested MPs (e.g., Boots et al., 2019), in addition to lack of detailed quantitative analyses of the data (e.g., He et al., 2018; Kim et al., 2020; Wang et al., 2019). Degradative processes of plastic in soil, termed ageing, may generate micro- and nano-size debris and may cause the release of toxic constituents and toxic additives, which may then enter in the food chain as a possible environmental and human health hazard. Here, a significant ecological impact has been attributed to nano-sized plastic particles (of less than 50 nm) in soil, because they are able to pass through cell membranes (Pathan et al., 2020). Recently, it has been demonstrated that PE with a particle size of 10 µm can already enter maize roots and may accumulate in maize tissue (root>leaf>stem), entraining plant growth inhibition (Zhang, Yang, et al., 2023). Wider ecological effects on plant biomass and root morphological traits caused by MPs in soil have been described via a legacy effect by soil microorganisms. Specifically, microbial inoculum taken from soil conditioned through previous MP treatment was amended to *Calamagrostis* plants. In comparison with inoculum from control soil, this led to both positive and negative plant–soil-feedbacks, including increased plant shoot mass and altered root traits (Lozano & Rillig, 2022).

Overall, upon addition of MPs to soils, changes in biogeochemical cycles (that are mediated primarily by soil microorganisms) have commonly been seen. Alterations in nitrogen cycling are brought about directly by adding MPs having nitrogen in their chemical structure. Indirect effects may result from modified microbial enzymes catalysing nitrogen cycling processes, changes in soil fauna and their decomposition activities, or alterations in soil physicochemical qualities. However, since most studies to date have been performed under laboratory conditions, the global effects of MPs on the nitrogen cycle are unknown (Riveros et al., 2022). As an example, the impact of plasticized PVC MPs on soil nitrogen cycling was found to mainly be a function of the phthalate present in it, while pure PVC was relatively inert under experimental conditions (Zhu et al., 2022). A significant impact of MPs on key pools and fluxes within the terrestrial carbon cycle has been suggested, however, in dependence of dose and MP type. Zang et al. (2020) found that MPs influenced assimilated ^{14}C allocation in soil (+71%) and CO_2 emission (+44%) and that β -glucosidase activity was suppressed by MPs, while some other carbon- and nitrogen-cycling related enzyme activities were not affected.

Despite numerous observed and expected negative effects, it has been stated that MPs in soils may also positively affect soil systems from some perspectives. Increased amounts of microbial biomass with the presence of MPs in soils are possibly due to fertilizing effects by extra input of substrates released from soil MPs within a specific threshold (Wei et al., 2022). However, above a certain threshold, MPs mainly exert poisonous effects on soil organisms (Teuten et al., 2009). Some studies have reported that addition of MPs may positively regulate soil physical properties, for example, by reducing bulk density and increasing water retention of soils, consequently proving beneficial to plant root growth (de Souza Machado et al., 2018; de Souza Machado et al., 2019; Zang et al., 2020). Presence of MPs in soils may also diversify the microbial habitat to support specific soil biota which are able to decompose plastics (McCormick et al., 2014). This may result in increases in rare microbial species feeding on plastic compounds that are less abundant in natural soils without plastics. There are also studies showing that existence of MPs in soils may promote soil carbon sequestration and increase soil organic carbon associated with minerals or small aggregates (Zhang & Zhang, 2020).

Due to the diverse ways in which soil organisms are impacted by MPs and at the same time are able to affect MP occurrence themselves and mediate effects on other soil biota, the proposition is emerging that MPs are unique among pollutants. In Helmberger et al. (2020), the authors call for a more explicitly ecological framing

of this novel issue for the soil environment. Thus, future research should stress potential interactions with soil communities, including MP formation via microbial and faunal fragmentation of large plastic debris and displacement within the soil system.

5 | BIODEGRADABILITY FOR PLASTICULTURE PRACTICES: REPLACING CONVENTIONAL MATERIALS TO TAKE CARE OF THE ENVIRONMENT

There are several factors that affect the amount of MPs generated by agricultural activities, their deposition and transport in the environment. Some of them are linked to anthropogenic activities (e.g., inefficient waste management practices), physical characteristics of plastic particles (e.g., shape, size and density), environmental climatic conditions (e.g., rain intensity and wind speed) or the topography of the environment (He et al., 2018; Karbalaei et al., 2018; Oliviero et al., 2019). In this context, practices linked to the intensive use of plastics in agriculture must be demanding regarding the safety of their plastic products since giving up their use is not an option due to the great advantages they bring to the sector. In this way, and thanks to plastic materials, traditional agriculture has taken a turn from being a marginal sector to becoming the main economic source of numerous traditionally disadvantaged towns and regions. The main solution strategies regarding the concept of prevention, the management of their waste and the possible degradation by environmental climatic reasons are focused on searching and development of low-impact materials. The objective is to select materials that have the least impact on the environment, for example, avoiding the use of formulations that contain toxic and dangerous substances, and/or using biodegradable bioplastics in cases where the environmental advantage is proven. Soil biodegradable polymers are increasingly used as alternative substitutes for agricultural applications. These products have been introduced into the agricultural sector due to scenarios where certain products need more complex recycling processes due to possible dirt and level of impurities (it is estimated that this level can be between 30% and 70%), present inefficient disposal practices that also involve the removal of organic and inorganic matter from the upper layers of the soil (contributing to depletion and desertification) and/or those that often cannot be recovered for management at the end of their shelf life.

Once the origin has been identified by the aforementioned activities, and to ensure the use of low-impact materials, work must be done to standardize analytical

methods for the detection and quantification of MPs in soils, in order to have a comprehensive understanding of their fate and dispersion in soils and ecosystems, and to develop best practices and global policies in the agricultural sector for sustainable development.

It is important to combine different procedures and analytical techniques so that a wide range of chemical formulations, types, morphologies and sizes of MPs are covered, ensuring the quality of the analysis. Sampling for the extraction of MPs is critical in the analysis process. There are guidelines to ensure that samples are homogeneous and representative (ISO 18400-102, 2017). The extraction of MPs can be carried out using techniques such as size-based separation, like microfiltration, and the isolation of MPs through density gradients, helping to isolate and concentrate MPs from complex environmental samples. Therefore, techniques are used based on the information desired. Spectroscopic methods, like FTIR and Raman, are often coupled with optical techniques, provide detailed morphological information, allowing for size and shape characterization of MPs. Chromatographic techniques, like Pyr-GC/MS and TD-GC/MS, play a crucial role in assessing the presence of additives, plasticizers, and associated contaminants in MP samples. Although it is always possible to combine all possible techniques, it must be considered that the maximum possible information must be obtained using the least number of resources because of the amount of sample is limited and most of the analytical techniques are destructive.

The integration of these diverse analytical approaches enhances our understanding of the distribution, composition, and potential ecological impact of MPs in the environment, contributing to informed decision-making to mitigate their adverse effects.

6 | CONCLUSION AND RECOMMENDATIONS

NETmicroplastic tackles the issue of MP in agricultural soils in a multi-actor and multi-stakeholder approach that encourages cooperation and opinion and data exchange. Together with our own very recent research (not yet published), the network's collected survey data cover the last four years and different population groups, evidencing a consistently high level of awareness and concern about MP pollution, in spite of the discussion being dominated by MPs in water/sea/ocean. Knowledge about MPs is mainly derived from and driven by the media and the internet, and most often focuses on MP pollution in the context of water bodies. Little attention has so far been paid to soil. Indeed, clear policy guidelines together with incentives for farmers are needed to

promote and change the current practice of plastic use (Hofmann et al., 2023) as also stated by MPs experts who ranked policy measures and education and awareness programmes the most promising ways to reduce plastic use, alongside 'plastic taxes', circular economy approaches and extended producer responsibility (Grünzner et al., 2023).

Another important result extracted from survey data implicates a lack of communication between producers, distributors and users of biodegradable and compostable collection aids on the one hand and composting facilities on the other. The majority of people think that biodegradable or compostable plastic collection aids can be thrown in the bio-waste bin, while composting facilities consider such collection aids to be a disturbing substance that needs to be separated before composting. Clear communication is needed here, as well as plastic bags with uniform patterns that can be easily recognized by AI-based scanning systems to automate the separation process, or to allow them not to be separated if certification has proven biodegradability in composting processes. Again, policies are needed to support these changes by providing a framework and establishing appropriate measures. This would lead to better quality compost and, in turn, greater acceptance and use by farmers.

According to the network's own investigations as well as related work, biodegradable plastic products are generally seen as a positive technological solution. However, biodegradable bioplastic products are not widely available and there is little knowledge among consumers and farmers about certification and what it means, both for biodegradable plastic collection aids and for mulch film. Here, policy is challenged to shed light on the certification jungle and to provide a legal framework for farmers willing to switch to using more environment-friendly equipment and devices in their production methods. For instance, more information is needed on the technical characteristics of biodegradable mulch films and their performance under field conditions. Therefore, biodegradable plastic products need to be evaluated under field conditions to demonstrate their technical quality and biodegradability compared to conventional plastic products to assure farmers of their good functionality and practicability. Risk assessment of conventional and biodegradable plastics in soil and the fate of different types of plastic materials in soil need to be substantiated based on real-life data. Furthermore, the behaviour of various types of plastic polymers in the soil environment, including the role of the soil biota, needs more investigation. In accordance with Catarino et al. (2021), we emphasize on the need for performing effect assessments and interaction studies for providing sufficient weight of evidence to reliably conclude on the risk of MPs in the environment.

AUTHOR CONTRIBUTIONS

Claudia Preininger: Conceptualization (lead); funding acquisition (lead); writing – original draft (equal); writing – review and editing (equal). **Evelyn Hackl:** Conceptualization (equal); writing – original draft (equal); writing – review and editing (equal). **Viktoria Stagl:** Writing – original draft (supporting).

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