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Review

Significance of Microplastics in Agricultural Soil

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Abstract: Microplastics (MPs) can effect terrestrial ecosystems (approximately 20% of the pollution rate), but it also strongly effect aquatic ecosystems, with an estimate of 80% of the marine pollution. In the present time, we are facing the fact that more and more agricultural land has been contaminated with MPs. Underground transport of MPs in the soil occurs through bioturbation with the help of plant roots and soil fauna, as well as plowing, soil cultivation, crop harvesting, water infiltration, etc. Literature data stated that the concentration of MPs in terrestrial ecosystems is multiple times higher than in the ocean, and due to this fact, the United Nations Environment Programme appealed for more research studies on the assumed effects.

Keywords: microplastics; pollution; agriculture; soil; interaction.

1. Introduction

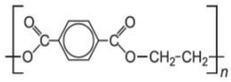
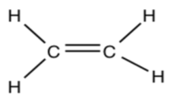
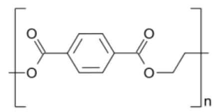
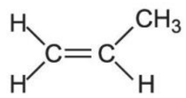
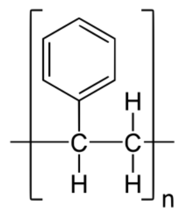
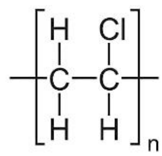
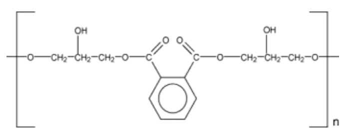
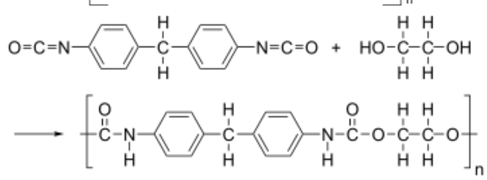
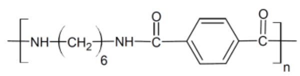
The use of plastics has become commonplace in all aspects of human life. The term "plastics" covers a wide range of concepts. Plastic consists of carbon, hydrogen, oxygen, and chlorine, which make up long-chain synthetic polymers and as such, have countless advantages, for instance, light weight, durability, efficiency, and low cost. Because of this, plastic has found wide application in various fields and meets basic needs in the production of clothing, cosmetics, toys, etc. In relation to this, it is one of the most common and largest pollutants on the planet, and the processes of plastic accumulation and fragmentation are constantly increasing [1]. It began to be more intensively used in the mid-19th century when polypropylene (PP), polyethylene (PE), and polyvinyl chloride (PVC) were created. Furthermore, plastic has been recognized as an inexpensive raw material with good characteristics, resistant to water, corrosion, and degradation. As a result, the intensity of its production is growing day by day in all areas. Plastic has become an alternative to metal, paper, and glass. In literature, the term "microplastics" (MPs) usually refers to all plastic particles smaller than 5 mm in diameter. MPS are found in almost every segment of the environment, making it an increasing problem that the human race faces. MPs can effect terrestrial ecosystems (approximately 20% of the pollution rate), but it also strongly effect aquatic ecosystems, with an estimate of 80% of the marine pollution. At present, we are facing the fact that more and more agricultural land has been contaminated with MPs. The sources of this pollution usually originate from improperly disposed waste material.

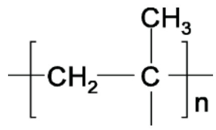
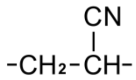
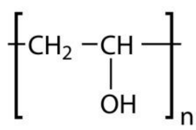
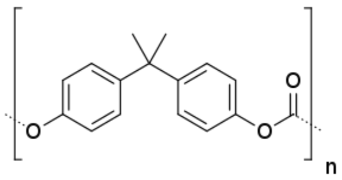
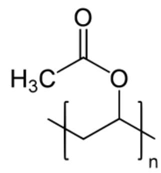
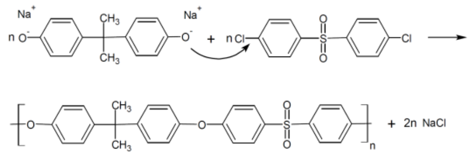
2. Types and chemical structure of the MPs

MPs have a wide range of chemical and physical properties. Plastic products are complex mixtures of one or more polymers, such as plasticizers, stabilizers, antioxidants, and others [2]. According to Zimmermann et al. [2], with more than 5000 different types of plastic on the market, the number of chemicals used in the plastic production is probably even higher.

Plastic materials often contain additives which make the plastic more flexible, colorful, or less flammable. These additives make MPs even more harmful to the environment, especially during the process of degradation. MPs are divided by their source into primary and secondary. Primary MPs are plastic particles originally produced in these sizes for direct use or as precursors to other products [3] and are released into the environment, for example, microbeads from personal care and cosmetic products [4], synthetic microfibers used in the textile and clothing industry [5], as well as the components of consumer and industrial goods. Secondary MPs are created by the breakdown of the larger plastic items into smaller particles product [6]. Secondary contamination with MPs is a result of fragmentation of plastic debris that has been present in the certain ecosystem for a long time and has been subjected to the environmental factors [7], chemical and mechanical processes [8], such as photolysis, abrasion, and degradation by microorganisms [9] (Table 1).

Table 1. The most commonly used plastic polymers susceptible to transformation into MPs by the degradation processes, their applications and chemical structures.

Polymer type	Properties and application	Chemical structure
Polyesters	Density of 1.24-2.3, so it is not biodegradable in water. Used in production of textiles, fibers, recording tapes, etc.	
Polyethylene (PE)	Density of 0.91-0.9, floats on water and is not biodegradable. Used in packaging, in bags, wire insulation and bottles.	
Polyethylene terephthalate (PET)	Density of 1.37-1.45, so it sinks in water and is not biodegradable. Used as a packaging material, in bottles for soft drinks.	
Polypropylene (PP)	Floats on water (density is 0.91) and is not biodegradable. Used in packaging materials, fibers, bottles, heavy microwave containers.	
Polystyrene (PS)	Non-biodegradable with a density of 1.01-1.04 (sinks in water). Used in packaging, styrofoam, items such as cutlery (forks, knives and spoons), trays, video cassette boxes, drinking glasses, toys...	
Polyvinyl chloride (PVC)	Non-biodegradable with a density in the range of 1.16-1.584, they are heavier than water. Used in construction, transparent packaging for clothing, bottles, floor coverings, synthetic leather and drainage pipes.	
Alkyd	Non-biodegradable and have a density of 1.67-2.1, and sink in water. Used in paints.	
Polyurethane (PUR)	Density ranges from 0.03-0.1 so it floats on water. Used in construction, foam, solid and flexible fibers. These compounds can be biodegraded by naturally occurring microorganisms.	
Nylon (Polyamide) (PA)	Density of 1.02-1.05, do not float on water. These compounds are biodegradable. Used in the automotive industry, in textiles,	

	fibers.	
Polymethyl methacrylate (PMMA)	Heavier than water with a density of 1.17-1.20. They are not biodegradable and can be recycled. Mainly used in electronics, as a substitute for glass, paints and household products.	
Polyacrylonitrile (PAN)	Density ranges from 1.09-1.20, so these compounds sink in water. Not biodegradable. Used in textile fibers and knitted shirts, sweaters, blankets and carpets.	
Polyvinyl alcohol (PVA)	Density of 1.19-1.31, so it sinks in water. Can be biodegraded with the help of fungi, gram-negative and gram-positive bacteria. PVA is used in textiles.	
Polycarbonate (PC)	Density varies from 1.20-1.22. Due to the presence of a phenyl group on both sides of the carbonate bond, enzymes cannot biodegrade PC. Used in electronic components, building materials, automotive, aircraft, railways and security components.	
Polyvinyl acetate (PVA)	Density of 1.19. It is used as glue for wood, wallpaper, envelopes, cigarette packaging. PVA is the basis of chewing gum.	
Polyethyl sulfones (PES)	Density of 1.31-1.34, high-performance thermoplastics, resistant to acids, bases, oils, fats and aliphatic hydrocarbons. These compounds have good optical clarity, insulating properties, moderate strength even at high temperature and are used in medical devices.	

3. Degradation of MPs in soil

Plastic degradation occurs due to the impact of sunlight, water, or environmental physical, chemical and biological factors. After some time, such microplastic particles break down into even smaller particles, and then are called nanoplastics (<100 nm in diameter). During degradation, additives slowly start to leach out of plastic particles into the soil, but more alarming is that they can also penetrate into the tissues of living organisms [10].

4. Sources of MPs pollution in agricultural soil

MPs have been the subject of research by scientists around the world in recent decades, with the largest number of studies focusing on pollution in aquatic environments, especially oceans. However, a large number of scientists believe that soil can contain much more MPs than oceans, which can have a negative impact on plants, soil flora and fauna, and therefore, consequently, on the food chain [11].

The sources of MPs pollution are numerous and MPs appearance, transport, and fate in the environment are influenced by various natural factors, as well as their physical-chemical properties [12]. Covering the soil with plastic film is an important agricultural technology that plays a key role in increasing crop yields and maintaining moisture in the soil. However, prolonged coverage and untimely recovery lead to a large amount of plastic residues in the soil. Over time, these residues break down into smaller pieces of plastic, which can reduce the quality of seeding, destroy soil structure, and have a negative impact on the organisms in the soil [13]. Significantly less attention has been devoted to the soil pollution with MPs, despite the fact that the amount of MPs released into the soil is 4-23 times greater than in the aquatic environments [14]. The sources of MPs in soil are diverse: irrigation with contaminated wastewater, wear and tear of machine tires, atmospheric deposition, use of organic fertilizers, application of sewage sludge, and plastic residue from greenhouses [15, 16].

5. MPs interaction with other pollutants

Furthermore, it is confirmed that MPs are excellent adsorbents of pesticides, polycyclic aromatic hydrocarbons (PAHs), and other hydrophobic toxic substances [17], effecting their assimilation and incorporation in animal and human tissue.

The use of plastic films and pesticides in agriculture is on the rise, causing the buildup of plastic waste and pesticide remnants in the soil. This accumulation poses a significant environmental problem as it endangers the life of earthworms, hinders enzyme activity and microbial diversity, and results in a loss of soil microbial carbon and nitrogen. Despite this, there is currently limited knowledge on the impact of pesticides on dissolved organic matter in the soil. Liu et al. (2019) [18] have investigated the impact of plastic waste, specifically MPs, on the effects of pesticides destiny in the soil. To conduct this analysis, they performed a 30-day soil incubation experiment, applying three different levels of the common herbicide glyphosate to the soil: 0 as a control (CK), 3.6 kg/ha^{-1} (G1), and 7.2 kg/ha^{-1} (G2). Additionally, they explored the impact of four different levels of glyphosate and MPs, specifically homopolymer polypropylene powder, which were co-added to the soil: 3.6 kg/ha^{-1} + 7% (w/w) (M1G1), 3.6 kg/ha^{-1} + 28% (w/w) (M2G1), and 7.2 kg/ha^{-1} + 7% (w/w) (M1G2), and 7.2 kg/ha^{-1} + 28% (w/w) (M2G2). The results of this study emphasized that glyphosate addition resulted in a slight increase in soil fluorescein diacetate hydrolase (FDAse) and phenol oxidase activities. While the addition of glyphosate significantly promoted the accumulation of dissolved organic phosphorus within the first 14 days, the M2 treatment decreased organic matter at day 30. Interestingly, M2G1 and M2G2 increased soil FDAse activity and promoted the accumulation of dissolved organic nitrogen and dissolved organic phosphorus in comparison to G1 and G2 respectively. In contrast, M1G1 and M1G2 benefited the dissolved organic nitrogen accumulation. The findings of this study indicate that when glyphosate is present in an environment with low levels of MPs, it can have a negative impact on the dynamics of dissolved organic carbon and dissolved organic phosphorus, leading to a loss of bioavailable carbon and phosphorus. Additionally, the interaction between glyphosate and high levels of MPs can also negatively impact dissolved organic nitrogen levels compared to glyphosate alone, which may contribute to a decrease in dissolved organic nitrogen.

Due to their small size, strong hydrophobicity, and large specific surface area, MPs can absorb toxic substances in soil, such as heavy metals [18]. In addition, in this way adsorbed heavy metals can migrate and potentially be released into the surrounding environment [19]. Therefore, MPs combined with heavy metals can pose a risk of synergistic environmental pollution, resulting in potentially harmful effects on soil organisms. De Souza et al. (2019) [20] and Hodson et al. (2017) [21] have discovered that MPs particles in soil adsorb organic pollutants (PAHs), potentially toxic metals, and chemicals that disrupt the endocrine system, which not only effects the health of the soil, but also transfers and incorporates in the food chain.

6. Impact of MPs on soil

The first scientist who stated that MPs in the soil effect its physical-chemical properties, soil functions such as density, bio-physical characteristics, microorganism activities, and plant growth and maturity, was Rillig in 2012 [22].

Although various ecotoxicological studies [23, 24] have been conducted, the real environmental risks of MPs are still subject to debate among researchers due to the inconsistency of MP concentrations and the uneven characteristics of the plastic used in the laboratory and originally collected samples from the nature or organism. MPs originated from the real environment vary in terms of their types, shapes, sizes, and compositions, which are directly related to their toxicity [25].

Li et al. (2022) [26], conducted a study at 24 sampling sites across three soil layers, on different plots, i.e. in greenhouses, open fields, and vegetable plots. Results showed that the most common sizes of soil MPs were 0.2-0.5 and 0.5-1.0 mm, the most common shape was film (85.93%), the most common color was white, and the main polymer was polyethylene (93.1%), indicating that most MPs came from the residual mulch degradation. The prevalence of MPs was highest in greenhouse plots (7763 ± 2773 particles/kg), followed by vegetable plots (4128 ± 2235 particles/kg), and lastly on crop fields (3178 ± 3172 particles/kg). There were no significant differences observed in the quantity of MPs in the 0-10 cm layer (1822 ± 1345 particles/kg), 10-20 cm layer (1566 ± 1139 particles/kg), and 20-30 cm layer (1309 ± 1028 particles/kg), suggesting that MPs may migrate deeper into the soil and are strongly influenced by soil management practices, water regime and burrowing activities of soil organisms. It has also been found that different crop characteristics and agricultural practices influence the prevalence and MPs migration in different types of agricultural soils, and consequently, their horizontal and vertical distribution. This research provides important data for future studies on MPs in terrestrial ecosystems, especially agroecosystems.

MPs that enter the soil are persistent environmental pollutants since soil can absorb, accumulate or transport it through the soil matrix [27]. The concentration of MPs in agricultural soils ranges from 0 to 165,000 particles per kg of soil [28].

The maximum concentration of MPs has been reported in agricultural land in Pakistan and amounted to 675 mg/kg [29]. According to a literature review, it is also noted that soils where sewage sludge is applied or irrigated with sewage water have higher amounts of MPs particles per kg of soil [30].

7. Impact of MPs on plants

As mentioned earlier, MPs are recognized as significant pollutants due to global climate changes, altering the soil properties and leading to increased mortality and oxidative stress in living organisms. Due to all these factors, it is expected that they also have a negative impact on the growth and development of plants. In addition, interactions with other global change factors, such as drought, can have an even greater impact on the MPs negative effects. Lehmann et al. (2022) [31] conducted a study to confirmed these claims, where the effects of polyester microfibers, arbuscular mycorrhizal (AM) fungi, and the plant reaction to the drought due to the negative impact of MPs were examined. The results indicated that in the presence of polyester microfibers, the aboveground biomass of *Allium cepa* is increased due to regular watering and under drought conditions. The treatment with AM fungus reached the highest level of biomass only in the drought conditions, however, the colonization of AM fungi increased under the contamination of microfibers, but the biomass did not increase when both, AM fungi and fibers, were present. This study points to an increasing amount of evidence that MP particles in the soil can affect the plant-soil system, as well as other organisms in the soil.

Li et al. (2021) [32] investigated the synergy of the root system growth and the migration of MPs in soil. MPs accumulate in the soil and it is assumed that they migrate vertically due to water infiltration, as well as the activities of fauna and root growth. This study included three crops, corn, soybean, and lupine, and the impact of their roots on plastic migration. The results showed that the crop roots had a small effect on the MPs migration when they were distributed in the surface layer of the soil. However, the corn root has shown slightly higher efficiency in moving MPs towards the surface layer of soil when its particles were distributed in the middle layer of the soil. This is because the corn root produces more pores and cracks in the soil profile than the roots of other crops. Additionally, a positive correlation has been observed between the number of MP particles and the tertiary root of the corn, with these results indicating the ability to retain MPs in the finer roots of the crop. According to the results, unlike the movement of MPs in the lower layers, which is permanently caused by water infiltration and soil fauna activities, crop roots carry out the MPs migration upwards and are responsible for MPs maintenance in shallow soil layers.

It has been proven that MPs in soil indirectly affect seed germination and plant growth, and their translocation in plants depends on the shape, size, and chemical properties of MPs [33]. Literature review has revealed that MPs enter the plant through the free space between root cells [34]. Also, according to De Souza Machado et al. (2019) [20], polystyrene in onions increases root biomass and total root length, while polyamide and polyester fibers significantly affect soil microbial activity and the elemental tissue composition. On the other hand, some studies showed that in maize crops, polystyrene and polylactic acid reduce root biomass [12], while polyester particles slow down nutrient uptake and plant growth [35].

In wheat crops, polystyrene increases the length and biomass of roots while reducing the size ratio between roots and shoots [36]. On the other hand, low-density polyethylene reduces the number of leaves and biomass, affecting the vegetative growth of plants [37]. Moreover, polyethylene also affects the antioxidant system in roots [38]. In bean crops, Jiang et al. (2019) [39] found that polystyrene reduces biomass and the activity of catalase enzymes, slowing down nutrient transport.

8. Impact of MPs on soil fauna

Earthworms are one of the most important living organisms in the soil, having the ability to maintain soil fertility and therefore playing a key role in sustainability. They maintain the physical and chemical properties of the soil by converting biodegradable materials and organic waste into nutrient-rich products. Additionally, they improve the plant residues decomposition in the soil, create soil porosity through their activities, contribute to the formation of humus, as well as organic matter [40, 41]. With increasing amounts of plastic and plastic waste, the living organisms in the soil are strongly disrupted. MPs in the soil affect the food supply of the soil fauna, causing an imbalance in their diet, which leads to reduced growth and reproduction, organ damages, and disturbances in metabolism and immune response. Several studies have shown that the MPs layer in the soil affects the growth of earthworms because it causes histopathological and immunological changes. MPs in the soil also cause intestinal and oxidative damage to nematodes [42, 43], resulting in a decrease in body length, survival rate, and reproductive capacity. The presence of MPs in the soil has a negative impact on the health of macrofauna (earthworms, snails), which convert organic matter and nutrients into a form that plants can use.

Due to their presence in the upper trophic levels of the food chains, worms such as *Eisenia fetida* (Savigny, 1826) and *Lumbricus terrestris* Linnaeus, 1758 are often used as bioindicators to assess critical thresholds for determining soil pollutants [44]. Since worms are also responsible for the main processes related to the soil fertility, these thresholds can also be used to analyze soil and determine when soil fertility loss will occur [45].

Ding et al. [46] revealed that MPs concentrations greater than 40 g/kg^{-1} negatively impact biomass and reproduction of the earthworms. Considering that MPs concentrations in some environments have reached over 67 g/kg-1, this study suggests that MPs may already be negatively affecting earthworm populations and, consequently, negatively impacting soil biodiversity. They also discovered that concentration is a dominant factor that affects the biomass and reproduction of worms, rather than the type of plastic material. Two types of biodegradable MPs (PLA and PPC) did not give better results than PE, which is non-biodegradable plastic.

Similar study was also conducted by Baeza et al. [47] on the *Lumbricus terrestris*, testing the impact of varied MPs concentrations (2.5; 5, and 7% w/w) on these organisms. The results showed that earthworms did not distinguish MPs from soil particles, and at high concentrations, MPs caused physical lesions on the surface of the earthworms' bodies as they were exposed to these concentrations, which induced the stress in animals, and lost of the protective mucus that lining their bodies.

Yu et al. [48] also investigated the impact of MPs at various concentrations on *Eisenia fetida*. They used two different soil types, and the study covered polyethylene (PE) and biodegradable polylactic acid (PLA) of different concentrations (0.5, 1, 2, 5, 7, and 14% w/w). The results of the research showed that the activities of the enzymes superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), glutathione S-transferase (GST), and acetylcholinesterase (AchE) were reduced after exposure to PE and PLA for 14 days, while the concentration of malondialdehyde (MDA), an indicator of oxidative stress, was increased. After 28 days, the levels of SOD, CAT, POD, AchE, and GST increased, while the level of MDA decreased. These changes indicated that the toxic effects of MPs depend on their concentration, rather than the type of particles or soil. PE had a greater harmful impact than PLA particles on the 14th day, but such a significant difference was not observed on the 28th day. Also, the gut microflora of *E. fetida* was not changed, but the prevalence of Actinobacteriota, Bacteroidota, Ascomicota, and Rozellomicota was altered. The results also showed that both conventional and biodegradable MPs equally induce oxidative stress in *E. fetida*, and pollution in different soil types did not differ much, indicating that the toxic effects caused by MPs are less dependent on particle type and soil type, and much more on the concentration of MPs in soil.

9. Conclusion

Underground transport of MPs in the soil occurs through bioturbation with the help of plant roots and soil fauna, as well as plowing, soil cultivation, crop harvesting, water infiltration, etc. [22]. Horton et al. [14] reported that the concentration of microplastics in terrestrial ecosystems is multiple times higher than in the ocean, and due to this fact, the United Nations Environment Programme (UNEP) appealed for more research studies on the assumed effects. On the other hand, it is necessary to deal with the problem of microplastics, which will most likely be considered in the draft of the Treaty on the Functioning of the European Union, which deals with the basic goals and principles of environmental protection policy, the implementation of which is primarily based on preventive actions [49].

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Conflicts of Interest: The authors declare no conflict of interest.

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