Biodegradable Microplastics and Plants

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Microplastics (MPs) pollution has emerged as one of the world's most serious environmental issues, with harmful consequences for ecosystems and human health. One proposed solution to their accumulation in the environment is the replacement of nondegradable plastics with biodegradable ones. However, due to the lack of true biodegradability in some ecosystems, they also give rise to biodegradable microplastics (BioMPs) that negatively impact different ecosystems and living organisms.

Keywords: biodegradable microplastics ; plants ; ecotoxicity

1. Introduction

Nowadays, several reviews have analyzed the interactions between nonbiodegradable microplastics and plants, discussing the phytotoxic effects given by MPs uptake [1][2][3]. The most common are plant growth suppression, mechanical damage to the root system, and MPs accumulation in edible parts, as well as the effect on soil properties and its microbiome. However, in response to exposure to microplastics, plants can activate defense mechanisms to reduce the negative impact [4]. Moreover, all these reviews agree that there is currently not much data on the subject and that more field trials are needed.

At the time (May 2023), 22 research articles have been identified from the Scopus and Web of Science databases investigating the interaction between biodegradable plastic particles and plants [5][6][7][8][9][10][11][12][13][14][15][16][17][18][19][20][21][22][23][24][25][26]. The survey methodology included queries in the Scopus and Web of Science databases for "biodegradable microplastics and plants". For better detail, the word "plants" was replaced by specific types of "corn", "soy", and "rice" from the articles found. Since, at the moment, this field of science is quite young, no time frame was set for the selection of articles. The criterion for inclusion in the review was the availability of results specifically on the effect of BioMPs on the plant itself. The exclusion criteria were as follows: study of nonbiodegradable microplastic particles, lack of an English version of the text. Also, commentaries, summaries, reviews, editorials, and duplicate studies were excluded.

For cultivating corn and soybeans, mulch film is used, which is gradually being replaced by a biodegradable [27][28]. Therefore, the study of the effect of BioMPs on the growth of these plants is in demand in the first place. Additionally, these plants are important for the human food chain. Corn is most popular in the regions of Central America and Africa [29]. Soy is one of the staple foods in Asia [30]. Furthermore, soybeans produce a huge amount of feed for livestock and birds due to their high protein content [31]. A change in the yield of these crops can have great consequences for humanity.

The most studied BioMPs were made of PLA and PBAT. These polymers, in fact, are the most common biodegradable substitute for LDPE in the production of mulching film for agriculture [32].

Regarding the size, the BioMPs under study can be classified into four size ranges, from particles smaller than 50 μm to 2 cm, all having a quite uniform size distribution. Since, currently, there is a lack of research to estimate the size of BioMPs particles formed in the soil, researchers can focus on the typical dimensions of the formed MPs, which, anyway, can differ in different worldwide regions [33][34]. In fact, some authors identified, quantified, and measured the sizes of the most commonly produced MPs in soils of specific regions, finding that, in the southwestern region of China, ca. 82% of MPs are in the size range of 50–250 μm [33], while in Switzerland the highest MPs concentrations are associated with particles of larger size 125–500 μm [34].

Since there are no exact data on the concentration of BioMPs in soils, researchers are mainly guided by data on the content of MPs. Initial quantitative estimates suggest that background concentrations may be as high as ~0.002% of the soil weight in Swiss nature reserves [35]. Levels > 7% by weight of soil have been reported in roadside soils near industrial areas [36]. In the analyzed articles, the most studied concentrations are in the range from 0.1 to 1 wt%. There are also descriptions of high BioMPs concentrations of about 10%. It is also worth noting that all the studies found were conducted in pots, except only one study [20]. This may introduce distortions in the results obtained. Field tests should be the next stage of research.

Thus, it can be noted that the field of studying the interaction of BioMPs with plants is young and very popular. Research is carried out on different plants with different materials and particle sizes. This will help to accumulate the amount of data and understand the general trends in the interaction of BioMPs with plants at different stages of life.

2. BioMPs Effects on Seed Germination, Root System Development, and Biomass Growth

Several authors investigated how BioMPs may affect seed germination and their early development since this interaction can have drastic effects on agricultural production yields. Serrano-Ruiz et al. examined the effect of biodegradable mulch film microplastic particles (based on PLA, PHB, and PBAT/starch and PLA/starch blends) in two greenhouse-scale pot assays on tomatoes (*L. esculentum*) and lettuce (*L. sativa*) seeds [5]. The authors' results provide evidence that BioMPs fragments did not affect germination but have the potential to interact with tomato and lettuce plants and alter plant development. The authors emphasize the danger of this since mulch film is usually used already at the stage of sprouts, not seeds.

The effect on the percentage of seed germination and growth is shown by Li and co-workers, who performed a pot experiment under field conditions using a biodegradable mulch film consisting of a PLA–PBAT blend and soybean (*Glycine max*) as a model plant [6]. With an increase in the concentration of microplastics based on PLA–PBAT, seed germination decreased. In the presence of BioMPs at concentrations of 0.1, 0.5, and 1 wt%, the germination rate was 50, 33, and 17%, respectively, whereas, in the control, the germination rate was 70%. The authors associated this with a change in soil properties and a slowdown in the absorption of water by seeds. However, no negative effect on the growth rate was found, and the highest rate was observed in samples with the addition of 1% BioMPs. A decrease in seed germination was also noted by Boots et al. [7] in a study performed on perennial ryegrass (*Lolium perenne*). With the addition of PLA, 6% fewer seeds germinated compared to the control. In the same study, the effect of PLA on shoot length was shown to be reduced by 19%. The authors give assumptions about the reasons for the decline in germination and development. On the one hand, this may be due to the clogging of pores in the seed capsule; on the other hand, soil microbes contribute to the decomposition of PLA into oligomers, which can interact both with seeds and change soil properties. Su and coworkers [8] demonstrated the effect of PLA and PBS BioMPs on the growth of edible algae (*Chlorella vulgaris*). Both types of BioMPs had a negative effect on the growth rate of algae, which depended both on the type of MPs and on the concentration. In the presence of 100 mg/L PLA and PBS, 47 and 36% fewer algae grew compared to the control. A similar degree of inhibition was achieved in the presence of PE at a concentration 10 times higher. The authors attribute this effect to the size of the particles, as well as their ability to biodegrade and the possible release of chemicals from MP particles.

Yu et al. [9] examined the effects of PLA BioMPs derived from biodegradable disposable masks on the germination and growth of winter grazing ryegrass (*Lolium perenne*). The experiments were carried out in pots, mixing the test soil with BioMPs, both in their original state and after artificial aging in different liquid media (alkaline solution at pH = 10, seawater, aquaculture water, and Fenton's reagents), at a concentration of ca. 1.2–1.3 g/cm^3. The authors reported that the presence of BioMPs generally reduces the germination rate of ryegrass seeds. With respect to the control, for which 95% of the seeds sprouted, in the presence of not-weathered particles, there was a reduction by 3 ÷ 8%, and, after their weathering in alkali, seawater, aquaculture water, and Fenton's reagents, the reduction was by 60%, 79%, 82%, and 53%, respectively. The results were attributed to the blocking of the pores in the ryegrass seed capsules by fine-fiber microplastics and bead-like particles.

Note that, despite the small amount of data, the effects of BioMPs on plant germination were always found to be nonpositive: neutral or negative. To date, there is no consensus on the reasons for this decrease in seed germination. The main proposed mechanisms are changes in soil properties, release of toxic products during decomposition, and blocking of seed pores. It can be assumed that large particles mostly affect germination by changing soil properties and releasing toxic degraded matter, whereas the smaller ones (for sizes around 300 microns and lower, as in articles [6][7][8]) can also enter the pores in the seeds blocking them.

Changing biomass, root system structure, and other plant-growth parameters can affect the yield. Therefore, it is necessary to trace the influence of BioMPs on these parameters. In the article by Liu et al., the mechanisms responsible for the effects of PBAT BioMPs on the biomass growth of Arabidopsis (*Arabidopsis thaliana*) have been investigated. The study demonstrated that the incorporation in the soil of PBAT BioMPs at a concentration of 2 wt% reduced the area of rosette leaves by two times compared to the control and decreased the plant biomass by 27% [10]. In addition, the number of pods per plant was about a third of normal, and both the production rate of reactive oxygen species (ROS) were indicative of oxidative stress and the activities of the key enzymes involved in ROS metabolism were significantly increased. The authors suggest that plant-growth suppression is due to the activity of microorganisms that degrade PBAT BioMPs, forming toxic compounds (adipic acid, terephthalic acid, and butanediol). However, this requires further research. In contrast, in another study by Yang et al. on corn seeds (*Zea mays* L. var. Wannuoyihao), PLA increased plant biomass at concentrations of 0.1 and 1 wt%; however, when the dose was increased to 10 wt%, the biomass of wheatgrass decreased to 40%, and the biomass of roots to 50% [11]. The authors present three possible pathways for the effect of BioMPs on plant growth: alteration of soil properties, alteration of soil microbiome and soil enzymes, and release of secondary metabolites during degradation. They suggest that some dose-dependent metabolites may be released during the microbial degradation of PLA, resulting in different effects on plant growth. In another study by the same research group, this also on corn seeds (*Zea mays* L. var. Wannuoyihao), the authors reported that PLA at a 10% concentration strongly inhibited corn growth, reducing the plant biomass and chlorophyll content, but had no significant effect at 0.1% and 1% doses [12]. Here, the toxicity was attributed to the release of toxic substances during the decomposition of particles, which alter the symbiotic microbial community with possible risks to soil–plant systems.

Different effects of the influence of PLA and PBAT were found in the publication by Cao et al. [13]. At a concentration of 2.5 wt%, PLA reduced the root length of wheatgrass (*Triticum aestivum*) by 39% and PBAT increased it by 72%. However, when the PLA concentration was 0.5%, the root length increased by 55%. Anyway, the changes depend not only on the type and level of biodegradable material but also on the type of plant. In another study, Lian et al. showed that when growing soybean (*Glycine max* L.) the root length was significantly reduced in the presence of 0.1% PLA but increased under 1% PLA, with a dose-dependent effect [14]. A similar alteration was observed in the levels of several antioxidative enzymes involved in ROS scavenging, which indicates the disruption of the antioxidant defense system of the soybean. The authors conclude that different PLA BioMPs concentrations had diverse impacts on the change of metabolites involved in plant growth, reasonably due to an alteration of the soil's microbial community.

The 0.1–10 wt% concentration range of PLA BioMPs was used by Liu et al. in interaction with corn (*Zea mays* L.) [15]. The article shows that the presence of 0.1% PLA does not affect the biomass of the corn sprout. However, 1% PLA, 5% PLA, and 10% PLA reduced the shoot biomass of corn by 32%, 63%, and 69%, respectively, in comparison with the control. A similar effect of reducing plant biomass in the presence of PLA BioMPs was also reported by Song et al., who used rice (*Oryza sativa* L. var. Yueguang) as a model plant [16]. The authors of both publications attribute this to the degradation of PLA and the release of water-soluble low-molecular-weight oligomers, which induce microbial immobilization and assimilation of essential nutrients and increase stress in plants.

Meng et al. showed that a mixture of PLA and PBAT in an amount of 1.5 to 2.5% reduced the biomass of the roots of beans (*Phaseolus vulgaris* L.), and at concentrations of 2 and 2.5%, the biomass of fruits and the sheet area, also [17]. At all concentrations, higher values of root length were noted, which correlated with the previous results. The authors suggest as possible reasons for this behavior the alteration of the soil microbiome due to BioMPs or the need for plants to increase the length of the roots to search for nutrients at depth.

The reduction in corn (*Zea mays* L.) biomass in the presence of PHBV microplastics was reported by Brown et al. [18]. A significant negative effect was noted already at concentrations equal to 1 wt%. Authors attribute this effect to the rapid influx of labile C substrates into the soil, leading to alleviation in metabolic C limitations.

In the articles referred to above, pristine BioMPs were used, which is easier from the viewpoint of the experiment, but shows a distorted result. Serrano-Ruiz et al. compared pristine and weathered BioMPs on two horticultural crop plants: tomato and lettuce [5]. The experiment showed that, when using weathered BioMPs based on PBAT + starch and PBAT + PLA, the plant biomass decreased from 37 to 76%, respectively. This effect was noted for both the tomato and lettuce. The authors attribute this effect to the accelerated release of toxic substances from the BioMPs particles. The authors also argue that it is necessary to use weathered particles to study phytotoxicity.

Qi et al. conducted a study about the effects on wheatgrass (*Triticum aestivum*) growth of two different plastic mulch film residues, one made of LDPE and the other one reported as “biodegradable” mulch film [19]. This “biodegradable” film consisted of starch, PET, and PBT in ratios of 37.1%, 44.6%, and 18.3%, respectively. The authors point out that this film cannot be considered fully biodegradable, but this composition is widely used in agriculture. The article showed that microplastics at a concentration of 1 wt% based on this “biodegradable” film showed a stronger negative impact compared to polyethylene. However, the disturbance caused by MPs was offset by the presence of earthworms in the soil. Unfortunately, no other studies on similar effects associated with earthworms and BioMPs were found.

Chu et al. conducted field trials on the effects of two shapes (fiber and powder) of pure PLA on oat (*Avena sativa* L. cv. Bayou 14) and soybean (*Glycine max* L. Merr. cv. Jizhangdou 2) for 5 months [20]. They report that BioMPs at 0.2 wt%, which is indicated as a realistic pollution level of agricultural soils, had no significant effect on soil enzyme activity, soil physicochemical properties (soil moisture content, pH, etc.), root characteristics, plant biomass, and yield. The authors draw encouraging conclusions that PLA BioMPs are not dangerous in the field for a period of up to several months.

Similarly, Souza et al. reported that PBAT BioMPs from mulch films, before and after photodegradation and biodegradation in soil, did not induce phytotoxicity in lettuce (*Lactuca sativa*) and were not cytotoxic and genotoxic for onion (*Allium cepa*) [21]. Anyway, they also stress the need for additional studies to complement the ecotoxicological impact assessment, as also suggested by the European Committee for Standardization—EN, 17033/2018 [37].

Thus, it can be noted that the effect of BioMPs on plants depends on several factors: the type of particles, the concentration, and the type of plant. Large concentrations (>2%) most often had a negative effect on plant and root biomass. Simultaneously, in almost all cases, an increase in the length of the plant root was noted. It can be assumed that this is due to the search for less polluted soil layers in depth or an increase in plant resistance since microplastic particles change soil parameters and make it looser.

It is also worth noting that no correlation was seen between BioMPs particle size and plant biomass. In general, the studied BioMPs particles had a size of up to 150 μm, and, in all cases, they had a negative effect on the plant and root biomass.

3. BioMPs Effects on Internal Processes of Plants

In addition to influencing external factors, BioMPs cause disturbances in the internal processes of plants. Most often, the presence of BioMPs leads to oxidative stress in plants. Liu et al. performed a study on Arabidopsis (*Arabidopsis thaliana* L. Heynh.) that, although not of any agronomic importance, is one of the most used model organisms for plant sciences [10]. The authors have shown that PBAT particles increased the rate of ROS production in the leaves of Arabidopsis after 14 and 28 days. Also, the presence of PBAT increased the content of malondialdehyde (MDA) after 28 days. Both of these factors indicate oxidation processes.

Also, an increase in the content of MDA and ROS in the presence of PBAT was reported by Yang and Gao [22]. In the shoots and roots of rice (*Oryza sativa* L.), they were induced significantly more than 2 months after sowing. However, the concentration of MDA and ROS was lower than with the addition of PE microplastic particles. The authors suggest that MPs and BioMPs affect plant growth through nitrogen metabolism and photosynthesis.

In addition to increased ROS and MOD concentrations, there have been reports of changes in peroxidase (POD) activity. POD is an antioxidant enzyme that functions in animal and plant physiological defense strategies against free radicals and ROS generated due to biotic and abiotic stresses [38]. Impairments in the work of the POD were reported by Lian et al. [14]. The addition of 0.1% PLA MP decreased POD activity by about 30%. The metabolomics study suggested that the significantly affected metabolic pathway is amino acid metabolism.

There are also data on changes in the process of photosynthesis in plants under the influence of PBAT. Yang and Gao noted the suppression of genes involved in photosynthesis, as well as antenna proteins in rice in the presence of PBAT [22]. In this regard, the rate of net photosynthesis decreased after two months of the experiment; however, this effect disappeared after 4 months of the experiment. This may indicate that with the development of the plant, the negative effects can be leveled.

Changes in the functioning of the corn (*Zea mays* L.) antioxidant system have been reported by Sun et al. [22]. The presence of the BioMPs mixture at concentrations of 1 and 10%, consisting of PBAT and PLA, increased the concentration of H_2O_2 in the corn leaves by three times compared to the control. However, similar to Yang and Gao [21], the authors showed that corn sprouts adapted to stress over time and regulated the activity of antioxidant enzymes.

Thus, it can be noted that in all the articles found the presence of BioMPs affected the antioxidant system of various plants. Generally, an increase in the concentration of ROS was noted, which indicates oxidation. There is initial evidence that plants can adapt to this by regulating the activity of enzymes. Also, oxidation may decrease as the plant grows.

4. Interactions of BioMPs with Heavy Metals and Effects on Plants

In addition to soil contamination with microplastic particles, there is the problem of the accumulation of heavy metals in it. To date, it has been shown that different types of MPs can adsorb heavy metals on their surfaces and facilitate their movement in the environment and into living organisms [39][40][41]. However, there is still no clear understanding of the interaction between MPs, heavy metals, and plants. On the one hand, some studies have shown that MPs can adsorb heavy metals and adhere to the root surface, and then, facilitate their penetration into plant roots through apoplastic or symplastic pathways [13][42]. However, MPs particles attached to the root surface can prevent the absorption of heavy metals by competing with heavy metals for adsorption sites on the root surface. Further, the results of studies on the interaction of BioMPs, heavy metals, and plants will be considered.

Most often, researchers reported on the effect of PLA-based MPs on the accumulation of heavy metals in roots without changing their concentration in shoots. The study by Lin et al. [24], performed on rice (*Oryza sativa* L.) as a model plant, showed that at a PLA concentration of 0.2 wt% and a Cd concentration of 1 mg/kg, Cd accumulated in the roots in an amount about 50% higher compared to the control. The authors hypothesize that the causes are alterations in soil pH and microbial communities due to the biodegradation of BioMPs. However, an opposite result was reported by Wang et. al. on the growth of corn (*Zea mays* L. var. Wannuoyihao) exposed simultaneously to MPs and Cd [12]. In their study, the authors showed that the presence of PLA MPs did not significantly change the Cd concentration in both roots and shoots except at the dose of 10%, to which the Cd uptake by the plant was appreciably reduced. They attributed this result to the decreased plant biomass due to severe phytotoxicity produced by the high-dose PLA MPs. A similar effect was reported by Liu et al., once again on rice [25]. However, the reduction in Cd levels in rice was already significant with 2% PLA microplastic. The difference in the result can be explained by the difference between the plants—rice or corn—under study; it can be assumed that different plants tolerate the interaction with BioMPs and heavy metals in different ways.

Metal accumulation in corn (*Zea mays* L. var. Wannuoyihao) was measured by Yang et al. [11], where the presence of PLA particles increased the Zn content in the roots in the presence of ZnO in the soil. Simultaneously, the Zn concentration in the shoots did not change, and, in some cases, even decreased. In the absence of ZnO in the soil, high PLA concentrations (10%) also reduced the Zn concentration in the shoots while increasing it in the roots. The authors suggest that a big concentration of BioMPs changes soil properties since they may attenuate the soil retention of heavy metals via a “dilution effect”, so ultimately increasing Zn accumulation by roots.

In a study investigating the interaction of BioMPs with antimony of different oxidation states (Sb(III) and Sb(V)) on wheatgrass seed development, it was found that, in addition to the type of material, the oxidation state of antimony affects the penetration into plants [13]. At high concentrations of 2.5%, PLA particles contributed to the accumulation of both Sb(III) and Sb(V) in the wheatgrass roots. Simultaneously, PHA particles at the same concentration did not show any effects when Sb(III) was introduced but significantly increased the Cd concentration in the presence of Sb(V).

Sun et al. used a mixture of PLA and PBAT microplastics to investigate the effects of BioMPs on photosynthesis, antioxidant defense systems, and arsenic accumulation in corn (*Zea mays* L.) seedlings growing in arsenic-contaminated soils [23]. They found that BioMPs are phytotoxic in As-contaminated soils at all considered concentrations (0.1, 1, and 10%), and the effects are higher than those given by polyethylene MPs used for comparison. Moreover, they proved that BioMPs at 10% reduced the leaf area and inhibited the accumulation of As in corn seedlings, maybe due to the inhibition of chlorophyll synthesis and photosynthetic rates in the corn seedlings’ leaves, and to BioMPs’ capacity to bound As in the soil, thereby reducing its bioavailability for the plant. The change in the bioavailability of HMs due to the presence of BioMPs in the soil was also reported in a large study by Li et al. [43].

Zhang et al. studied the effects of different types of MPs, made of biodegradable and nonbiodegradable polymers, on Cr accumulation and toxicity to cucumber (*Cucumis sativus* L.) in hydroponics, keeping cucumber sprouts in various solutions containing MPs or BioMPs and Cr(VI) [26]. MPs, regardless of the type, changed the accumulation of Cr, plant growth, and the defense system of cucumber plants upon treatment with Cr(VI), which was mainly determined by the MP type and particle size. PLA-based BioMPs reduced the accumulation of Cr(VI) due to the high adsorption capacity for Cr(VI) in the solution. This demonstrates that BioMPs particles can inhibit HMs not only in soil but also in water.

Thus, based on a few articles, it can be concluded that BioMPs can affect the accumulation of heavy metals in plants. The main places of accumulation are the roots of the plant. However, the effect depends on a combination of several factors: the type of metal, the type and concentration of the BioMPs, as well as the plant itself. It can be noted that the presence of heavy metals and BioMPs in the soil has a double effect. On the one hand, cases were recorded in which the concentration of HMs in plants decreased. On the other hand, the presence of BioMPs had a negative effect on plants and reduced germination and biomass. Therefore, the area of interaction between heavy metals and BioMPs needs to be explored further to systematize the possible effects and understand the risks. In this area, further research is needed to be able to better systematize the effects obtained.

Possible negative effects in the interaction of BioMPs and plants are presented in **Figure 1**. At the stage of germination, the presence of BioMPs in the soil can reduce the germination of seeds and cause delays in the development of the plant. In grown plants, BioMPs can adversely affect biomass and the area of leaves and cause violations in the operation of the antioxidant system. Thus, it is necessary to continue research in this area and the development of new standards for the disposal of biodegradable plastics.

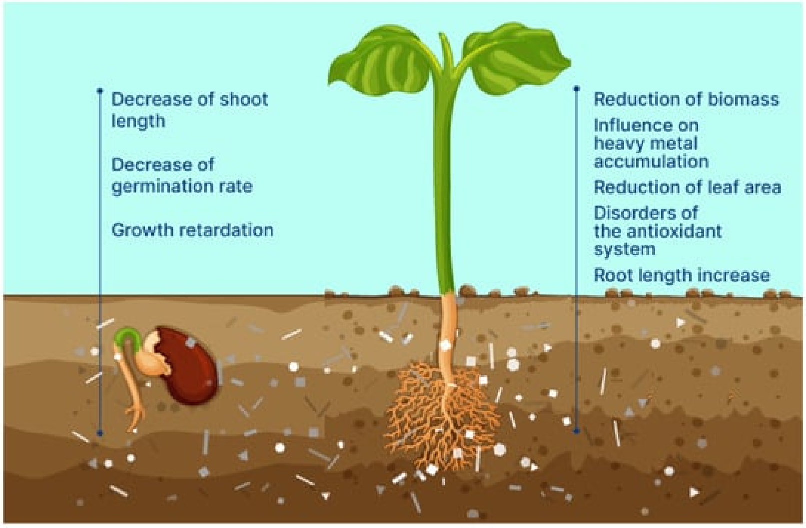

Figure 1. Potential negative influence on plants by biodegradable microplastics.

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