Science of the Total Environment 791 (2021) 148333

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Review

Review of the toxic effect of microplastics on terrestrial and aquatic plants

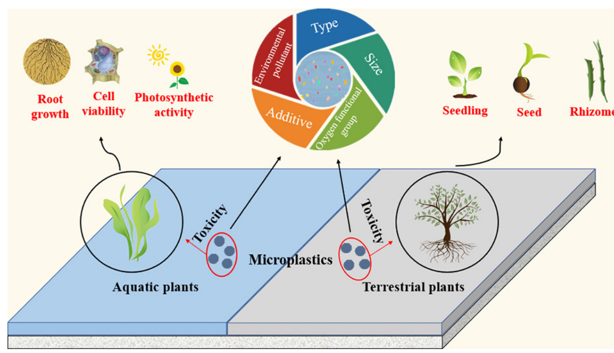
Jianhua Ge [a,1], Huang Li [a,b,1], Peng Liu [b,*], Zhiping Zhang [a,b], Zhuozhi Ouyang [b], Xuetao Guo [b,*]

[a] School of Earth and Environment, Anhui University of Science & Technology, Huainan 232001, China
[b] Key Laboratory of Plant Nutrition and the Agri-environment in Northwest China, Ministry of Agriculture, College of Natural Resources and Environment, Northwest A & F University, Yangling 712100, China

HIGHLIGHTS

- Physical injury of MPs to plants correlated to their type, size and oxygen groups.
- Secondary risk including additives and MP-derived products were reviewed.
- The seeds and rhizomes of plant are more sensitive to MPs.
- Toxicity difference of MPs on terrestrial and aquatic plants was compared.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 9 April 2021
Received in revised form 4 June 2021
Accepted 4 June 2021
Available online 7 June 2021

Keywords:
Microplastics
Plants
Toxicity
Size
Additives

ABSTRACT

As a new pollutant, microplastics (MPs) exhibited more and more significant influence on the organisms in the environment. Especially, the effects on the growth and development of plants by MPs attracted wide attentions in recent period. In the review article, we summarized the important influences of MPs on terrestrial and aquatic plants. The properties, including type, size and oxygen-containing group of MPs on their physical injures toward plants were critically reviewed, which were significantly correlated to the toxicity to plants. The secondary risks of MPs including the additives and MP-derived organic products and the adsorbed environmental pollutants to plants were clearly revealed. The hydrophobic organic pollutants released from MPs showed significant chemical effects on the plants. We also outlined the effects of MPs to the various regions (e.g. the seed and rhizome) of plants and compared the toxic difference of MPs on terrestrial and aquatic plants. Generally, the seed and rhizome of plants were susceptible to MPs, and the effects of MPs on terrestrial and aquatic plants were different. The review paper improves the understanding of potential toxicity of MP themselves and the released and adsorbed chemicals to plants in the environment.

Contents

* Corresponding authors.
E-mail addresses: pengliu@nwafu.edu.cn (P. Liu), guoxuetao2005@nwafu.edu.cn (X. Guo).
[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.scitotenv.2021.148333
0048-9697/

1. Introduction

According to the data from Plastics Europe, the global output of plastic products reached 359 million tons in 2018, where the output of plastic products in China reached 8.3 million tons in 2019 from the China Plastics Processing Industry Association (Shiu et al., 2020). Every year, 4.8 to 12.7 million tons of plastic are released into water bodies (Galloway et al., 2020). Under the influence of mechanical abrasion and environmental oxidation (UV, heat, chemical and biological processes), large plastics would be decomposed into smaller sized particles (Ryan et al., 2009; Thompson, 2014). In these particles, microplastics (MPs) and nanoplastics (NPs) are likely the most numerous plastics in the environment. Currently, 5 mm and 1 μm were widely selected the upper size limits of MPs and NPs, respectively, defined by the National Oceanic and Atmospheric Administration of the United States and the studies of Hartmann et al. (2019) and Gigault et al. (2021). The widespread existence of MPs as emerging pollutants in the environment has attracted more and more attentions (Cole et al., 2011). In addition to the fragmentation of macroplastics, the direct release of microbeads or microfibers from personal care products or washing clothes was also the main source of MPs in the environment (Atugoda et al., 2021).

MPs are ubiquitous contaminants of emerging concern in aquatic and terrestrial ecosystems (Zhang et al., 2021a, 2021b). The release of MPs in the environment can cause harm to organisms (Teuten et al., 2009). MPs are particularly harmful to the soil and affect the growth and development of plants, thereby posing potential risks to human health (Rillig et al., 2019). Sludge composts may act as a vehicle of MPs into soils and then enter soil biota, which in turn influence the spread of MPs in the environment (Zhang et al., 2020). Meanwhile, MPs can change the structure and properties of soil and the performance of plants. The changes of MPs on the physicochemical properties of soil will adversely affect the root properties, growth and nutrient absorption of plants (de Souza Machado et al., 2018; Wan et al., 2019; Xu et al., 2019). So far, there is a lack of systematic review information on the effects of MPs on plants (Chae and An, 2018). Numerous studies validated that MPs delayed the germination of seeds, reduced plant growth, and induced the ecotoxicity and genetic toxicity of plants, etc. (Bosker et al., 2019; Jiang et al., 2019; Qi et al., 2020), which largely depended on the type and dosage of MPs (Wang et al., 2020).

As we all know, plants are the initial source of energy and organic matter in all ecosystems. MPs in the soil are migrated and accumulated in plants, and then transported into human through the food chain, ultimately posing risks to the ecological environment and human health (Cole et al., 2011). Therefore, it is of great significance to review the effects of MPs on plants. The review article firstly summarizes the potential harm of MP themselves to plants based on their inherent properties (e.g. types, size and oxygen-containing groups). Then, the secondary risks of MPs including the additives and MP-derived organic products and the adsorbed environmental pollutants to plants were revealed. We also outlined the effects of MPs to the various regions (e.g. the seed and rhizome) of plants and compared the toxic difference of MPs on terrestrial and aquatic plants. Plants are divided into terrestrial plants and aquatic plants. Terrestrial plants play an important role in the ecological environment. Aquatic plants play an important role in freshwater ecosystems. For example, they provide energy for major producers in the food chain and other species. Habitats and shelters, and reduce suspended solids (Cremona et al., 2008; Gross et al., 2001; Gurnell et al., 2006). The review article would systematically improve the understanding of inherent and secondary toxicity of MPs to plants, providing insights and implications for future studies on potential risk of MPs to organisms in the environment.

2. Methodology

The keywords “microplastic and plants” OR “microplastic and plants” OR “microplastic and Terrestrial plants” OR “microplastic and Aquatic plant” OR “microplastic and Seed” OR “microplastics and Seedling” were selected to retrieve the publications in Web of Science from its inception (1950) to May 2021. Here, 87 records including 65 research and review articles were found. Then, we made a selection of the publications based on the title and abstract, where the records about effects of microplastics on phytotoxicity.

3. Physical injures of MPs to plants

The physical injures of MPs to plants were dependent on the properties of MPs, e.g. the type, size and oxygen-containing functional groups, which were plotted in Fig. 1.

3.1. Concentration and type of MPs

Previous works demonstrated that the rhizome biomass of rice exposed to PS MPs decreases with the increased concentrations of PS MPs (Wu et al., 2020). In addition, MPs can affect the biophysical properties of the soil, further causing the changes in biomass, tissue element composition, root traits of plants and soil microbial activity, where effects were critically dependent on the types of particles (de Souza Machado et al., 2019). For example, the polyester (PES) fibers and polyamide (PA) triggered different effects on plant properties and functions by altered soil structure and moisture dynamics (de Souza Machado et al., 2019). However, fibers had a more diverse compositions including PP, polyethylene terephthalate (PET) and polyacrylonitrile (PAN) (Zhang et al., 2021a, 2021b). The stem biomass of rice exposed to PS MPs was decreased, and the effect was increased with the concentration of PS MPs (Wu et al., 2020). And the similar case occurred for polytetrafluoroethylene (PTFE) (Dong et al., 2020). Also, studies

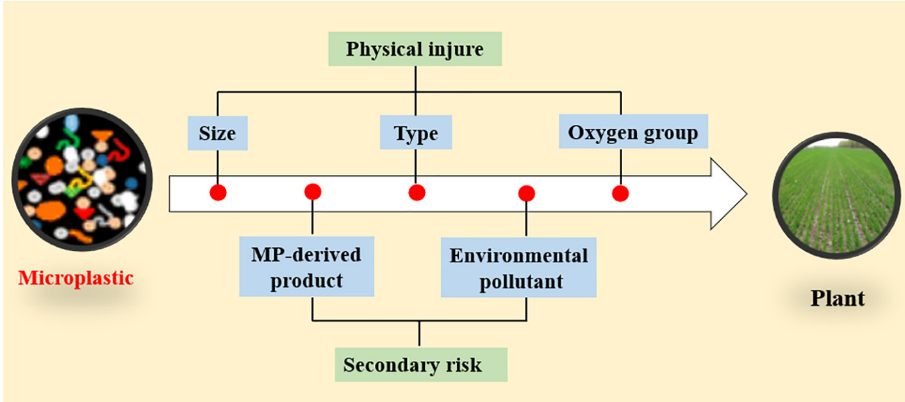


Fig. 1. Physical injure and secondary risk of MPs to plant.

validated that PS affected the characteristics of onions, e.g. increase in the total root length of onions and reduce in the average root diameter of allium plants (de Souza Machado et al., 2019). A recent study has shown the effects of four different exposure groups of MPs including polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC) and mixtures (PE + PVC) on L. *sativum* (Pignattelli et al., 2020). In the group with plants + PE, each biological property including the biological parameters (i.e., seed germination inhibition percentage, plant height, number of leaves, and fresh biomass yield) and oxidative stress (i.e. the levels of hydrogen peroxide, glutathione and ascorbic acid) were negatively affected after exposure for 6 days. The exposure group of PE + PVC showed a low impact on the biomass yield of plants. The combined group of PP and PE exhibited a negative impact on the germination rate, leaf number and biomass, while the height is mainly affected by PE + PVC. When plants are exposed to PE, the germination inhibition rate is 55%, and when they are exposed to PE + PVC, the germination inhibition rate is 55.3%, indicating that PE is the most toxic to plants. In the plants treated with PE + PVC, the photosynthetic pigment value was as low as 0.15 mg/g. Compared with the control plants, the plant treated with PE + PVC had the lowest proline content of 22 μg/g (Pignattelli et al., 2020), which further indicated that PE MPs showed less impact on plants (de Souza Machado et al., 2019; Wang et al., 2020). Compared to PE, polycarbonate (PC) MPs have been demonstrated to possess a negative impact on tomato germination, root and seedling length, and germination speed after 7 days of exposure. However, the toxic effects were different among MP exposure amounts, where the inhibition on plant germination was 16%, 27% and 55% in the matrix containing 0.1%, 1% and 10% PC MPs (Pflugmacher et al., 2020). Studies have also found that the height and biomass of plant corn after PE treatment are significantly reduced (Urbina et al., 2020).

Various types or forms of MPs also showed different toxic effects on plants. For example, the seed germination of perennial *perennial ryegrass* were 45%, 74% and 75% after being exposed to high-density PE, clothing fiber and biodegradable polylactic acid (PLA) MPs, respectively (Boots et al., 2019), which indicated the higher toxicity of PLA MPs. A recent study investigated the effects of ethylene-vinyl acetate copolymer (EVA), linear low-density polyethylene (LLDPE) and polymethyl methacrylate (PMMA) MPs on the seed germination of wheat seeds. Results showed that the order of inhibitory effect of MPs on wheat seed vigor index was LLDPE > EVA > PMMA from strong to weak. Overall, all types of MPs at low and medium concentrations (<500 $mg \cdot L^{-1}$) have an inhibitory effect on the germination rate of wheat seeds with the inhibition rate ranges from 2.86% to 20%, while the exposure group at high concentrations (1000 $mg \cdot L^{-1}$) has a certain promotion of seed germination rate (Lian Jiapan and Weitao, 2019).

The toxic effect of MPs on aquatic plant algae cells is also related to its type and concentration. The chlorophyll content of microalgae treated with PS MPs decreased, and the chlorophyll of microalgae treated with high-concentration PS MPs exhibited a greater decline than low-concentration PS MPs (Zhang et al., 2017). Furthermore, PE MPs significantly affected the growth of freshwater aquatic plant duckweed roots, and smaller particles even reduced the viability of root cells (Kalcikova et al., 2017). The high concentration (50 $mg \cdot L^{-1}$) of PVC also has a negative effect on algae photosynthesis, because the chlorophyll content and photosynthetic efficiency both decrease under the PVC treatment (Zhang et al., 2017). PP MPs can make heteroaggregates composed of microalgae, MPs and extracellular polysaccharides, thereby affecting the growth of microalgae (Lagarde et al., 2016).

3.2. Size

The toxic effect of MPs on organisms largely depends on their particle sizes (Ziajahromi et al., 2018). Generally, the toxic effect of MPs on organisms increases with the decrease of particle size (Sjollema et al., 2016). The ingestion of MPs with small (17.23 ± 3.43 mm) and large sizes (34.43 ± 13.09 mm) by *macropora* were 8.3 times and 5.2 times higher than that of MPs (39.54 ± 9.74 mm) ($p < 0.05$), respectively. The survival rate of *moina* exposed to small and large MPs (20% and 60%, respectively) was significantly lower than that of individuals exposed to microsomal debris (90%). In particular, the small-sized MPs significantly ($p < 0.05$) reduced the algae ingestion (from 95% to 76%), body length (from 4.20 mm to 3.98 mm) and the number of offspring (from 109 to 74) (An et al., 2021).

Some studies have found that the particle size of MPs is an important factor in determining plant growth performance (De la Torre Roche et al., 2015; Jiang et al., 2019). For example, the negative effect of 5 μm PS MPs on the germination of tomato seeds is lower than that of 100 nm PS NPs (Liao et al., 2019). Overall, the germination rate of seeds increases as the size of the plastic decreases (Bosker et al., 2019), and low particle size and high concentration PE MPs show obvious toxicity to the growth of plants (Liu et al., 2019a).

In addition to effects, the biomass and catalase activity of broad bean root decreased under treatment of 5 μm PS MPs, and the superoxide dismutase (SOD) and peroxidase activity increased significantly under exposure of 100 nm PS. Also, 100 nm PS NPs exhibited higher genetic toxicity and oxidative damage to broad beans than 5 mm PS MPs. 100 nm PS NPs can accumulate in broad bean roots and are most likely to block cell connections or cell wall pores to transport nutrients (Jiang et al., 2019). Compared with MPs, NPs have a significant toxicity effect on plants, where the dry weight of roots increases, the length of the main stem is shortened, and the biomass of stems and roots and the length of side branches increase, which reduces the signal-to-noise ratio of plants (van Weert et al., 2019). Under the treatment of three different sizes of plastic particles (0.05, 0.5 and 4.8 μm) on terrestrial plants (cress), the adverse effects increase as the size of the plastic increases. The germination rate of seeds exposed to 4800 nm NPs was decreased from 78% of the control to 17% of the highest exposure (Bosker et al., 2019). Studies have also shown that MPs of different shapes change the characteristics of plants. Fibrous MPs increase plant shoot quality by about 27%, film by 60%, foam by about 45%, and debris by about 54% (Lozano et al., 2021).

In aquatic plants, the size of MPs also affects the toxicity to phytoplankton and microalgae (Zhang et al., 2017). Larger-sized MPs have less impact on the growth and photosynthesis of microalgae, while smaller-size MPs have a greater impact on microalgae (Lagarde et al., 2016). Under the treatment of three different sizes (0.05, 0.5 and 6 μm) of PS MPs, 0.05 μm of MPs have a higher negative impact on the growth of microalgae (up to 45%), whose adverse effects increase as the particle size decreases (Sjollema et al., 2016). Because the small size of MP particles adsorbed on the surface of algae cells will produce a shading effect, so it can reduce the light absorption efficiency and photosynthesis efficiency of the algae (Schwab et al., 2011). When the aquatic plant *Utricularia vulgaris* was treated by PS MPs, the chlorophyll *a* content of small MPs (1 mm) was 45% higher than that of large MPs (5 mm). However, the chlorophyll *b* content of large-sized MPs (5 mm) was 58% higher than that of small-sized MPs (1 mm). When plants were exposed to small-sized MPs (1 and 2 mm), the level of lipid peroxidation in plant leaves (MDA) content was 107–127% higher than that of large-sized MPs (5 mm). The catalase level of small size MPs (1 and 2 mm) was higher than that of large size MPs (5 mm) (Yu et al., 2020).

3.3. Oxygen-containing functional groups

When the plastic is released into the environment, some environmental factors, e.g. the physical effects, temperature fluctuations, degradation caused by UV, microbial degradation and weathering will result in the aging of the plastics, and the aging MPs will make their properties more complicated (de Souza Machado et al., 2019). Fu et al. (2019) reported that the UV-irradiated PVC MPs has a higher inhibitory effect on the growth of microalga *Chlorella vulgaris* (22–35%) than *virgin ones* (10–28%). This is due to the higher SSA and surface enhancement of the adsorption performance of aged MPs on microalgae cell (Fu et al., 2019).

The MPs via weathering may gather together with phytoplankton and cause adverse impact (Jahnke et al., 2017). In terms of adsorption, accumulation and toxicity, the surface chemistry of PS particles is a key parameter that determines the behavior, ecological interaction and impact of PS particles on marine plants. The negatively charged PS MPs would inevitably form micro-scale aggregates in the culture medium, and their influence on the growth of microalgae does not exceed 5×10^4 μg/L. These negatively charged nanoparticles were found to be adsorbed on microalgae, and the positively charged PS MPs were found to be nano aggregates in both media, leading to inhibition of algae growth (Bergami et al., 2017). The adsorption of PS NPs also hinders the photosynthetic activity of algae and promotes the production of reactive oxygen, which mainly depends on the physical and chemical properties of the plastics and the morphology and biochemical properties of the algae. Adsorption is conducive to positively charged plastics, including electrostatic interactions, hydrogen bonds, and hydrophobic interactions between algae and plastics (Priyanka Bhattacharya et al., 2010).

Oxygen-containing groups produced by MPs that have undergone the weathering process in the environment affect the polarity, hydrophilicity, electrostatic interaction and hydrogen bonding of the MPs surface, thereby affecting the adsorption of organic pollutants (Liu et al., 2019b; Liu et al., 2020; Muller et al., 2018; Wang et al., 2020; Zhang et al., 2018), further indirectly affect the toxic effects of MPs on plants. The positively charged plastic particles are attracted by the cellulose components of plant cells due to static electricity. The surface roughness of the plant cellulose provides a large number of binding sites for the plastic particles, thereby enhancing the adsorption of MPs (Priyanka Bhattacharya et al., 2010). PE MPs have a higher affinity for negatively charged surfaces (Kalcikova et al., 2017).

4. Secondary risks of MPs to plants

4.1. Additives and MP-derived organic products

As shown in Fig. 1, the release of additives and oligomers detected in plastics may cause serious pollution (Suhrhoff and Scholz-Bottcher, 2016), the overall risks are seemingly enhanced by aging process due to the high ingestion by organisms, the strong interaction with pollutants and the release of MP-derived organic compounds (Liu et al., 2021a, 2021b). The additives released by MPs cause serious toxic hazards to the embryonic development of *Perna perna* (Gandara et al., 2016), and MPs additives will inhibit the activity of *Amphibalanus amphitrite* larvae and increase mortality (Li et al., 2016). Normally, MPs in the environment contain various chemical additives, including plasticizers, flame retardants, antioxidants and stabilizers. Some of these organic compounds are added from the plastic manufacturing process. These pollutants are easily released from MPs into environment to result in chemical risks on surrounding organisms. A breeding experiment showed that PCBs can be transferred from contaminated plastic to striped shearling water chickens (Teuten et al., 2009). Additives also pose a potential threat to the terrestrial environment because they can seep into groundwater and/or surface water from waste disposal sites (Teuten et al., 2009). Additives and oligomers released from MPs might be absorbed by organisms to further cause severe toxicity (Browne et al., 2013; Jang et al., 2016; Wathsala et al., 2018). Also, plasticizers can inhibit the germination rate of plant seeds and cause programmed death of plant cells (Liu et al., 2013). Release of PS MPs additives increase the photosynthetic activity of four types of microalgae (Dina salina, Scenedesmus, Chlorella, and Echinococcus rod-shaped) (Chae et al., 2020).When plants contact or inhale MPs, MPs can provide a viable way to transfer the absorbed chemical pollutants and released additives to their tissues, causing potential health risks (Campanale et al., 2020; Koelmans et al., 2016).

4.2. Environmental pollutants

MPs can be used as carriers of pollutants in the environment (Alimi et al., 2018). Due to its microscopic size, hydrophobic surface, large specific surface area and strong fluidity, MPs have high affinity for hydrophobic organic pollutants and adsorb them from the environment (E.L. Teuten et al., 2007; Ng et al., 2018; Velzeboer et al., 2014; Wang et al., 2018; Y. Mato et al., 2001). In addition, MPs can be used as a carrier to transport heavy metals in the environment (Brennecke et al., 2016; Godoy et al., 2019), adsorption of heavy metals by MPs mainly ascribed to the surface property (e.g. oxygen-containing groups and size) and the adhered biofilm and charged minerals (Liu et al., 2021a, 2021b). The interaction between MPs and metal pollutants may lead to changes in plant performance and symbiotic relationships, thereby affecting plant ecosystems (Wang et al., 2020). PE and PLA, and cadmium (Cd) on plant performance and arbuscular mycorrhizal fungal community were investigated in an agricultural soil (Wang et al., 2020). PE and Cd exhibited a significant effect on plant root biomass, while PLA and Cd did not interact significantly. The coexisting Cd and MPs on the dominant arbuscular mycorrhizal fungus (AMF) produced a slight but important interaction (Wang et al., 2020). In general, plant growth and AMF community varied with the type and dose of MPs, Cd and their interactions. High-dose PLA produces stronger phytotoxicity. The simultaneous presence of MPs and Cd can jointly change the plant performance and root symbiosis to bring additional risks to agricultural ecosystems and soil biodiversity (Wang et al., 2020). The adsorption of pollutants by MPs depends on several factors, such as the physical and chemical properties of the polymer, the solution chemistry of the surrounding environment, the degree of weathering and temperature, and the hydrophobicity of the adsorbent (Alimi et al., 2018; Huffer and Hofmann, 2016), The degradation and fragmentation of original plastic can increase the exposed surface area, thereby increasing the adsorption capacity for environmental pollutants (Alimi et al., 2018). However, the information about the combined risks of MPs and adsorbed environmental pollutants is severely lack, which should be given more attentions in the next studies.

5. Potential toxicity to terrestrial and aquatic plants

5.1. Terrestrial plants

As previously reported, MPs could adversely affect the physiological function of terrestrial plants, mainly on seed and rhizome, and so on. Detailed effects of MPs with different types, sizes and concentrations on various plants were summarized in Table 1.

5.1.1. Seed

As shown in Table 1, the germination rate of plant seeds is an important index to evaluate the effect of MPs on phytotoxicity (Khalid et al., 2020). MPs not only change the structure of the soil, but also reduce the germination rate of plant seeds (Boots et al., 2019). Studies have found that MPs can inhibit the germination rate of celery seeds, mainly because MPs block the gaps in the seeds through physical action (Bosker et al., 2019). However, high-concentration MPs can actually promote and restore the germination rate of wheat seeds (Lian Jiapan and Weitao, 2019). The reason why high-concentration MPs exhibited a certain effect on the recovery of wheat seeds may be that the adsorption and absorption of MPs by wheat seeds depends on the charge, particle size and agglomeration of MPs (Alimi et al., 2018; Weber et al., 2018; Ziajahromi et al., 2018). For example, the increased particle size of the agglomerated MPs hinders the adsorption of MP particles by the seeds. PE MPs with low particle size and high concentration showed obvious toxicity to the growth of mung bean seedlings, reducing the dry weight, fresh weight, root length, shoot length and moisture content of the seedlings (Liu et al., 2019a). The physical blocking of the pores in the celery seed sac by the MPs is the reason that affects the germination. As the size of the plastic increases, the effect becomes more and more significant (Bosker et al., 2019).

Plasticizer is a kind of organic matter which can increase the plasticity of synthetic resin and synthetic rubber. The plasticizer in the MPs can inhibit the germination of wheat seeds. With the increase of the plasticizer concentration, the germination rate of wheat seeds gradually decreases (Liu et al., 2013). After 72 h of 1500– 1800 $mg \cdot L^{-1}$ of plasticizer treatment, the germination rate is only 58% and 44%. Plasticizer also showed effect on the activity of SOD during the germination of wheat seeds, where after treatment with a low concentration of plasticizer (0– 900 $mg \cdot L^{-1}$), the SOD activity tends to decrease firstly and then increase with time, while after being treated with a high concentration of plasticizer (1200– 1800 $mg \cdot L^{-1}$), the SOD activity showed a gradual decrease with the treatment time. In the case of a certain plasticizer treatment time, with the increase of the plasticizer concentration, the SOD activity change trend is not obvious (Liu et al., 2013).

5.1.2. Rhizome

Studies have shown that the root length was decreased with the increased concentration of PS MPs in the experiment of hydroponics. Under soil culture conditions, PS MPs inhibit root growth (Liao et al., 2019). Furthermore, the addition of PE MPs significantly reduces wheat root biomass and reduces wheat root-branch ratio (Qi et al., 2018). This could be explained by that the adsorption of MPs in the corn rhizosphere leads to a significant decrease in transpiration, nitrogen content and growth (Urbina et al., 2020).

When the particle size of MPs becomes smaller, the specific surface area will increase. Then, it will be easier to attach to plant roots or seed surfaces, and further inhibit water absorption. At the same time, the decreased size of MPs affects the respiration of seeds, thereby affecting the growth and development of roots and buds (Liu et al., 2019a). Due to low density, MPs reduce the soil bulk density and improve soil aeration, which further increase the penetration of roots in the soil, so that the quality of the stems and roots of plants at the community level decreases with drought. This phenomenon become seriously obvious with the increased addition of MPs and ultrafine fibers (Lozano and Rillig, 2020). Since both PS MPs and cellulose cell walls are highly hydrophobic, the hydrophobic effect makes PS MPs adsorb on the surface of the roots, affecting the development of plant roots (Nel et al., 2009).

Studies have found that nanoparticles can migrate to the roots and other parts of plants (Ma et al., 2010), which has a toxic effect on plants. The effects of nanoparticles on plants include cell damage, reactive oxygen species (ROS) production, reduced photosynthesis and germination, blocked pores or channels and damage to deoxyribonucleic acid (DNA) structure (Tripathi et al., 2017). As similar in size with nanoparticles, NPs might also accumulate on the cell wall surface of hydroponic corn seedling roots, thereby inhibiting the growth of corn roots, leaf growth and transpiration (Asli and Neumann, 2009).

PS MPs can be absorbed by the mucus (highly hydrated polysaccharides) secreted from the root caps of lettuce and be adhered to the root surface (Table 1). A part of MPs accumulated in the roots can enter the vasculature of the stems and leaves of plants (Li et al., 2019). MPs absorbed by the roots may reach other parts of the plant through root pressure and transpiration tension (David E. Salt et al., 1995; Lu et al., 2008). MPs can also enter the wheat through the cracks in the sprout parts of the lateral roots of the wheat. The plastic particles are then transported from the root to the shoots, and the transpiration rate promotes the absorption of the plastic particles by the wheat (Li et al., 2020).

5.2. Aquatic plants

In addition, MPs are toxic to aquatic plants (shown in Table 2). The movement of phytoplankton on the surface water may adsorb and absorb MPs (Prokin et al., 2015). The sorbed MPs might reduce the length of main buds of rooted large plants, inhibited the root growth, photosynthetic activity and cell viability of freshwater phytoplankton. The sorption on the surface of the roots of the phytoplankton duckweed might further hinder the growth of the roots, resulting in a reduction in the length of the roots (Kalcikova et al., 2017; van Weert et al., 2019). Marine phytoplankton are quite sensitive to smaller-sized plastics and actively modify the chemical composition of exopolymeric substances (EPS) to cope with the pollution stress. The release of protein-rich EPS was found to facilitate aggregate formation and surface modification of plastic particles, thereby affecting their fate and colonization (Shiu et al., 2020).

Several studies demonstrated that the interaction and physical damage of MPs and phytoplankton microalgae may be responsible for the toxic effects of MPs on algae (Table 2). Although alage did not belong to plant, both of them shared photosynthesis. The important property suggested that the potential impact of MPs on the photosynthesis efficiency of algae can provide some information for the impact of MPs on plants. Based on previous works, MPs can affect the photosynthesis of algae through adhesion to the surface of vascular plants and thus gathering around to inhibit their photosynthesis (Besseling et al., 2014; Dovidat et al., 2019). Therefore, most microalgae contaminated with MPs show decreased cell abundance in culture (Cunha et al., 2019). MPs adsorbed in cell surface of microalgae could restrict the transfer of energy and substances between cells and the environment, thereby inhibiting the growth of algae (Zhang et al., 2017). The adsorption of MPs will hinder the photosynthesis of algae, and the exchange of light and air between cell and external environment will be blocked by MPs (Priyanka Bhattacharya et al., 2010). The heterogeneous aggregation of particles and algae will precipitate in the algae and affect the growth of the algae (Ma et al., 2015). PS MPs embedded in the cell wall of algae

Table 1
Various impacts of MPs on terrestrial plants.

Plant		Microplastic			Exposure time	Toxic effect	Reference
Species	Part	Type	Size	Concentration			
Hydroponic Maize	Rhizosphere	PE	3 μm	0.0125 and 100 mg L^{-1}	0.67 d	The nitrogen content and growth of plants are significantly reduced, impairing the absorption of water and nutrients.	Urbina et al., 2020
Vicia faba	Rhizosphere	PS	5000, 0.1 μm	10, 50, 100 mg L^{-1}	2 d	Broad bean root biomass and catalase activity decreased, while SOD and peroxidase activities increased significantly.	Jiang et al., 2019
Wheat and lettuce	Rhizosphere	PS, PMMA	0.2, 2.0, 5.0, 7.0 and 10.0 μm	0.5, 5 and 50 mg L^{-1}	10 d	By entering the mode of cracks in the part where the lateral roots appear, the microplastics are effectively absorbed.	Li et al., 2020
Zea mays L. var.	Rhizosphere and seed	PE, PS	100–154 μm	0%, 0.1%, 1%, and 10% (*w/w*)	30 d	Reduced the dry weight of rhizomes, resulting in a decrease in total dry weight.	Wang et al., 2020
Festuca brevipila and Holcus lanatus, et al.	Rhizosphere	PET	30 μm	0.4% concentration	60 d	At the community level, the quality of stems and roots increases with the increase of MPs.	Lozano and Rillig, 2020
Lolium perenne, A. rosea	Rhizosphere and seed	HDPE, PLA	102.6, 65.6 μm	1 mg/ g soil sample	30 d	When exposed to PLA, fewer seeds germinate. With the increase of PLA, the branch height decreases. The biomass of roses exposed to HDPE was significantly reduced.	Boots et al., 2019
Myriophyllum spicatum and Elodea sp	Rhizome	PS	0.05–0.19, 20–500 μm	Micro-PS: 0.1, 0.3, 1, 3 and 10%; nano-PS: 0.03, 0.1, 0.3, 1 and 3%	21 d	NPs increase plant rhizome dry weight and biomass, shorten main stem length, increase relative growth rate and increase lateral stem length.	van Weert et al., 2019
Triticum aestivum	Rhizosphere	LDPE	4000–10,000, 50–1000 μm	1% (*w/w*)	139 d	The total plant biomass is significantly reduced, affecting the development of the rhizosphere.	Qi et al., 2020
Triticum aestivum	Rhizome	PS	0.1, 5 μm	0, 10, 20, 50, 100 and 200 mg·L^{-1}	Hydroponics: 6d; Soil culture: 10d	High concentrations of PS inhibited the elongation of wheat roots and stems. With the increase of PS content, the content of photosynthetic pigment and soluble protein in wheat leaves increased first and then decreased, SOD activity decreased, and catalase activity decreased first and then increased.	Liao et al., 2019
Zea mays L. var.	Rhizome	PE, PLA	100–154 μm	0, 0.1%, 1% and 10% (w/w)	30 d	PE has no obvious. Phytotoxicity to corn, and 10% PLA reduces corn biomass and leaf chlorophyll content.	Wang et al., 2020
Oryza sativa L.	Seedlings and rhizome	PS	<50 μm	50, 250 and 500 mg L^{-1}	21 d	With the increase of PS concentration, the reduction of rice stem biomass is more obvious.	Wu et al., 2020
rice seedlings	Seedling and rhizome	PS, PTFE	10 μm	40, 100 and 200 mg L^{-1}	7 d	Rice biomass decreases with the increase of PS and PTFE concentrations in the growth medium, reducing the net photosynthetic rate, chlorophyll fluorescence and chlorophyll content of rice.	Dong et al., 2020
Wheat	Rhizosphere	PET	<2000 μm	50 g L^{-1}	1 d	PET particles can be used as carriers to transfer heavy metals to the rhizosphere of wheat.	Abbasi et al., 2020
L. sativum	Seed and leaf	PP, PE, PVC, PE + PVC	≤125 μm	0.02% (w/w)	21d	PE: Every biological feature is negatively affected. PE + PVC: All traits except biomass production have negative effects. PP: Negative effects on germination rate, number of leaves and biomass.	Pignattelli et al., 2020
Triticum aestivum	Seeds, leaf and rhizosphere	PE	50–1000 μm	1% (w/w)	13 d	In the process of wheat vegetative growth and reproductive growth, MPs will affect the above-ground and underground parts of wheat plants.	Qi et al., 2018
Lepidium sativum L.	Seeds、seedlings、rhizosphere	PC	3000 ± 1000 μm	0.1%, 1.0% and 10% (w/w)	7 d	The length of germination, roots and stems, and the calculated germination rate index are negatively affected.	Pflugmacher et al., 2020
Lactuca sativa	Leaf, rhizosphere	PS	0.2, 1.0 μm	50 mg L^{-1}	14 d	PS can be absorbed by the roots of lettuce and enriched in large amounts, then migrate from the roots to the upper part of the ground, and accumulate and distribute in the stems and leaves.	Li et al., 2019
mung bean	Seed, seedling, root	PE	0.023–0.88 μm	0.1, 1, 10 and 100 mg/g	5 d	When the exposure concentration is 100 mg/g, it has a significant inhibitory effect on the growth and water absorption of mung bean seedlings.	Liu et al., 2019a
Allium fistulosum	Root, leaf	PA, PE, PP, PET	PA: 15–20 μm, PE、PP: 2000 μm, PET: 222–258 μm	2.0% of soil	60 d	MPs can alter plant root traits, affect plant leaf traits and total biomass.	de Souza Machado et al., 2019
Triticum aestivum L.	Seed, seedling	EVA, LDPE, PMMA	0.05 μm	0, 10, 100, 500 and 1000 mg·L^{-1}	7 d	Low and medium concentrations have an inhibitory effect on the germination rate of wheat seeds, and high concentrations have a certain promoting effect. At 10 mg·L^{-1}, only LDPE significantly inhibited wheat germination.	Lian Jiapan and Weitao, 2019
Lepidium sativum	Seed	Polymer	0.05, 0.5, and 4.8 μm	10^6–10^{10} particles·L^{-1}	3d	Germination rate is significantly reduced, through the increase of plastic size, adverse effects increase	Bosker et al., 2019
Triticum aestivum	Seed	Plasticiz-ers	300–1800 mg·L^{-1}		3d	Plasticizers have a significant effect on the germination rate of wheat seeds and can inhibit the germination of wheat seeds	Liu et al., 2013

Table 2
Various toxic effects of MPs on aquatic plants.

Plant	Microplastic			Exposure time	Toxic effect	Reference
	Type	Size	Concentration			
Chaetoceros neogracile,Tisochrysis lutea	PS	2000 μm	39.6 mg L^{-1}	35 d	The distribution of MPs in algae cultures depended on the type and physiological state of the algae.	Long et al., 2017
Utricularia vulgaris	PS	1, 2 and 5 μm	15, 70 and 140 mL^{-1}	7 d	The growth rate and functional traits of leaves was significantly inhibited, high ecotoxicity and oxidative damage induced.	Yu et al., 2020
Lemna minor	PE	4–12 μm	0, 10, 50 and 100 mg L^{-1}	7 d	The root growth was significantly affected through mechanical blocking.	Kalcikova et al., 2017
Spirodela polyrhiza	PS	0.05, 0.5 μm	10^2, 10^4, and 10^6particles·mL^{-1}	5 d	MPs particles adsorbed to the roots of freshwater vascular plant but do not impair growth.	Dovidat et al., 2019
Chaetoceros Neogracile,Rhodomonas salina	PS	2 μm	5500 microbeads mL^{-1}	0.25 d	The sinking rate of diatom aggregates is reduced, while the sinking rate of cryptophyte aggregates increases.	Long et al., 2015
Dunaliella tertiolecta Thalassiosira pseudonana	PS	0.05, 0.5 and 6 μm	25 and 250 mL^{-1}	3 d	The growth of microalgae was negatively impacted, and the adverse effects increase as the size decreases.	Sjollema et al., 2016
Spirodela polyrhiza S. polyrhiza	PS	0.05 and 0.5 μm	10^2 to 10^6 particles mL^{-1}	5 d	The adsorption of MPs to multiple grasses causes the transfer of MPs to different herbivorous species in the ecosystem.	Dovidat et al., 2019
Thalassiosira pseudonana, Skeletonema grethae, Phaeodactylum tricornutum, Dunaliella tertiolecta	PS	0.055, 1 and 6 μm	10^{-4} to 250 mg L^{-1}	2d	Marine phytoplankton are quite sensitive to smaller-sized plastics and actively modify their EPS chemical composition to cope with the stress from pollution. The release of protein-rich EPS was found to facilitate aggregate formation and surface modification of plastic particles, thereby affecting their fate and colonization.	Shiu et al., 2020

will cause physical damage to the surface and negatively affect the growth of microalgae (Zhang et al., 2017). MPs can form aggregates with phytoplankton (Long et al., 2017), thereby accelerating the sedimentation of phytoplankton (Long et al., 2017). Positively charged plastic particles have stronger adsorption of phytoplankton cell walls than negatively charged MPs, destroying the cell walls of algae cells and inhibiting photosynthesis (Nolte et al., 2017). MPs can cause oxidative stress in algae cells, leading to an increase in the content of ROS in cells. The increase in ROS in cells can cause lipid peroxidation and destroy the structure of cell membranes, leading to collapse of the cell membrane skeleton, distortion and deformation of the cell membrane. The weakening or even loss of selective permeability affects normal growth and metabolism processes such as the exchange of substances inside and outside the cell (Xia et al., 2015).

6. Conclusions and perspective

As a new type of pollutants, MPs are easy to be absorbed by plants and can accumulate in the food chain because of their small particle size, large quantity, wide distribution, plasticizer and carrier of pollutants. This review article systematically describes the inherent and secondary toxicity of MPs to plants. The physical injures of MPs were correlated to the inherent properties of MPs induced by the types, size and oxygen-containing groups. The secondary toxicity was mainly resulted from the additives and MP-derived organic products and the adsorbed environmental pollutant. Also, the toxicity mechanisms of MPs to terrestrial and aquatic plants were summarized, where the permeation, adsorption or absorption of MP particles in plant cell, and ROS generation by MPs were the main mechanisms to the toxicity of MPs to plants. In general, the studies on the effects of MP on plants is relatively scarce, and most of them focus on the absorption of MPs by plant seeds, seedlings and roots. In the selection of plants, most researches are done on terrestrial plants, mostly concentrated on crops, so that the current review article have certain limitations. In order to provide insight into the effects and toxicity of MPs on plants, the focus and direction of future research can be as follows:

(1) Since almost all MPs in nature have undergone the aging process, the surface morphology and adsorption properties of MPs have undergone significant changes. The additives and small molecular products released by the MPs have a huge impact on the toxicity of plants. The potential effects of filtrate produced in the aging process of MPs on plants cannot be ignored.
(2) MPs can be used as carriers of pollutants and the aging process can also change the adsorption performance of MPs. Therefore, studying the joint toxicity of MPs with adsorbed different pollutants on plants is also a future research direction.
(3) Many more different types of plants should be selected as the target plant to investigate the toxic effect of MPs.
(4) Studying the toxic effects of MPs on other parts of plants, such as plant leaves, branches and stems is encouraged. The mechanism of MPs affecting plant growth and development is also the focus of future research.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The author acknowledge the financial support from the Ph.D start-up fund of Northwest A&F University (No. Z1090220186), Postdoctoral Science Foundation of China (No. 2020M680160) and National Natural Science Foundation of China (No. 41977307).

References

Abbasi, S., Moore, F., Keshavarzi, B., Hopke, P.K., Naidu, R., Rahman, M.M., Oleszczuk, P., Karimi, J., 2020. PET-microplastics as a vector for heavy metals in a simulated plant rhizosphere zone. Sci. Total Environ. 744, 140984.
Alimi, O.S., Farner Budarz, J., Hernandez, L.M., Tufenkji, N., 2018. Microplastics and Nanoplastics in aquatic environments: aggregation, deposition, and enhanced contaminant transport. Environ. Sci. Technol. 52 (4), 1704–1724.
An, D., Na, J., Song, J., Jung, J., 2021. Size-dependent chronic toxicity of fragmented polyethylene microplastics to Daphnia magna. Chemosphere 271, 129591.
Asli, S., Neumann, P.M., 2009. Colloidal suspensions of clay or titanium dioxide nanoparticles can inhibit leaf growth and transpiration via physical effects on root water transport. Plant Cell Environ. 32 (5), 577–584.

Atugoda, T., Vithanage, M., Wijesekara, H., Bolan, N., Sarmah, A.K., Bank, M.S., You, S., Ok, Y.S., 2021. Interactions between microplastics, pharmaceuticals and personal care products: implications for vector transport. Environ. Int. 149, 106367.

Bergami, E., Pugnalini, S., Vannuccini, M.L., Manfra, L., Faleri, C., Savorelli, F., Dawson, K.A., Corsi, I., 2017. Long-term toxicity of surface-charged polystyrene nanoplastics to marine planktonic species Dunaliella tertiolecta and Artemia franciscana. Aquat. Toxicol. 189, 159–169.

Besseling, E., Wang, B., Lurling, M., Koelmans, A.A., 2014. Nanoplastic affects growth of S. obliquus and reproduction of D. magna. Environ. Sci. Technol. 48 (20), 12336–12343.

Boots, B., Russell, C.W., Green, D.S., 2019. Effects of microplastics in soil ecosystems: above and below ground. Environ. Sci. Technol. 53 (19), 11496–11506.

Bosker, T., Bouwman, L.J., Brun, N.R., Behrens, P., Vijver, M.G., 2019. Microplastics accumulate on pores in seed capsule and delay germination and root growth of the terrestrial vascular plant Lepidium sativum. Chemosphere 226, 774–781.

Brennecke, D., Duarte, B., Paiva, F., Caçador, I., Canning-Clode, J., 2016. Microplastics as vector for heavy metal contamination from the marine environment. Estuar. Coast. Shelf Sci. 178, 189–195.

Browne, M.A., Niven, S.J., Galloway, T.S., Rowland, S.J., Thompson, R.C., 2013. Microplastic moves pollutants and additives to worms, reducing functions linked to health and biodiversity. Curr. Biol. 23 (23), 2388–2392.

Campanale, C., Massarelli, C., Savino, I., Locaputo, V., Uricchio, V.F., 2020. A detailed review study on potential effects of microplastics and additives of concern on human health. Int. J. Environ. Res. Public Health 17 (4).

Chae, Y., An, Y.J., 2018. Current research trends on plastic pollution and ecological impacts on the soil ecosystem: a review. Environ. Pollut. 240, 387–395.

Chae, Y., Hong, S.H., An, Y.J., 2020. Photosynthesis enhancement in four marine microalgal species exposed to expanded polystyrene leachate. Ecotoxicol. Environ. Saf. 189, 109936.

Cole, M., Lindeque, P., Halsband, C., Galloway, T.S., 2011. Microplastics as contaminants in the marine environment: a review. Mar. Pollut. Bull. 62 (12), 2588–2597.

Cremona, F., Planas, D., Lucotte, M., 2008. Biomass and composition of macroinvertebrate communities associated with different types of macrophyte architectures and habitats in a large fluvial lake. Fund. Appl. Limnol./Archiv für Hydrobiologie 171 (2), 119–130.

Cunha, C., Faria, M., Nogueira, N., Ferreira, A., Cordeiro, N., 2019. Marine vs freshwater microalgae exopolymers as biosolutions to microplastics pollution. Environ. Pollut. 249, 372–380.

De la Torre Roche, R., Servin, A., Hawthorne, J., Xing, B., Newman, L.A., Ma, X., Chen, G., White, J.C., 2015. Terrestrial trophic transfer of bulk and nanoparticle La2O3 does not depend on particle size. Environ. Sci. Technol. 49 (19), 11866–11874.

de Souza Machado, A.A., Lau, C.W., Till, J., Kloas, W., Lehmann, A., Becker, R., Rillig, M.C., 2018. Impacts of microplastics on the soil biophysical environment. Environ. Sci. Technol. 52 (17), 9656–9665.

de Souza Machado, A.A., Lau, C.W., Kloas, W., Bergmann, J., Bachelier, J.B., Faltin, E., Becker, R., Gorlich, A.S., Rillig, M.C., 2019. Microplastics can change soil properties and affect plant performance. Environ. Sci. Technol. 53 (10), 6044–6052.

Dong, Y., Gao, M., Song, Z., Qiu, W., 2020. Microplastic particles increase arsenic toxicity to rice seedlings. Environ. Pollut. 259, 113892.

Dovidat, L.C., Brinkmann, B.W., Vijver, M.G., Bosker, T., 2019. Plastic particles adsorb to the roots of freshwater vascular plant Spirodela polyrhiza but do not impair growth. Limnol. Oceanogr. Lett. 5 (1), 37–45.

Fu, D., Zhang, Q., Fan, Z., Qi, H., Wang, Z., Peng, L., 2019. Aged microplastics polyvinyl chloride interact with copper and cause oxidative stress towards microalgae Chlorella vulgaris. Aquat. Toxicol. 216, 105319.

Galloway, T., Haward, M., Mason, S.A., 2020. Science-based solutions to plastic pollution. One Earth 2 (1), 5–7.

Gandara, E.S.P.P., Nobre, C.R., Resaffe, P., Pereira, C.D.S., Gusmao, F., 2016. Leachate from microplastics impairs larval development in brown mussels. Water Res. 106, 364–370.

Gigault, J., El Hadri, H., Nguyen, B., Grassl, B., Rowenczyk, L., Tufenkji, N., Feng, S.Y., Wiesner, M., 2021. Nanoplastics are neither microplastics nor engineered nanoparticles. Nat. Nanotechnol. 16 (5), 501–507.

Godoy, V., Blazquez, G., Calero, M., Quesada, L., Martin-Lara, M.A., 2019. The potential of microplastics as carriers of metals. Environ. Pollut. 255 (Pt 3), 113363.

Gross, E.M., Johnson, R.L., Hairston Jr., N.G., 2001. Experimental evidence for changes in submersed macrophyte species composition caused by the herbivore Acentria ephemerella (Lepidoptera). Oecologia 127 (1), 105–114.

Gurnell, A.M., van Oosterhout, M.P., de Vlieger, B., Goodson, J.M., 2006. Reach-scale interactions between aquatic plants and physical habitat: river Frome, Dorset. River Res. Appl. 22 (6), 667–680.

Hartmann, N.B., Huffer, T., Thompson, R.C., Hassellov, M., Verschoor, A., Daugaard, A.E., Rist, S., Karlsson, T., Brennholt, N., Cole, M., Herrling, M.P., Hess, M.C., Ivleva, N.P., Lusher, A.L., Wagner, M., 2019. Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris. Environ. Sci. Technol. 53 (3), 1039–1047.

Huffer, T., Hofmann, T., 2016. Sorption of non-polar organic compounds by micro-sized plastic particles in aqueous solution. Environ. Pollut. 214, 194–201.

Jahnke, A., Arp, H.P.H., Escher, B.I., Gewert, B., Gorokhova, E., Kühnel, D., Ogonowski, M., Potthoff, A., Rummel, C., Schmitt-Jansen, M., Toorman, E., MacLeod, M., 2017. Reducing uncertainty and confronting ignorance about the possible impacts of weathering plastic in the marine environment. Environ. Sci. Technol. Lett. 4 (3), 85–90.

Jang, M., Shim, W.J., Han, G.M., Rani, M., Song, Y.K., Hong, S.H., 2016. Styrofoam debris as a source of hazardous additives for marine organisms. Environ. Sci. Technol. 50 (10), 4951–4960.

Jiang, X., Chen, H., Liao, Y., Ye, Z., Li, M., Klobucar, G., 2019. Ecotoxicity and genotoxicity of polystyrene microplastics on higher plant Vicia faba. Environ. Pollut. 250, 831–838.

Kalcikova, G., Zgajnar Gotvajn, A., Kladnik, A., Jemec, A., 2017. Impact of polyethylene microbeads on the floating freshwater plant duckweed Lemna minor. Environ. Pollut. 230, 1108–1115.

Khalid, N., Aqeel, M., Noman, A., 2020. Microplastics could be a threat to plants in terrestrial systems directly or indirectly. Environ. Pollut. 267.

Koelmans, A.A., Bakir, A., Burton, G.A., Janssen, C.R., 2016. Microplastic as a vector for Chemicals in the Aquatic Environment: critical review and model-supported reinterpretation of empirical studies. Environ. Sci. Technol. 50 (7), 3315–3326.

Lagarde, F., Olivier, O., Zanella, M., Daniel, P., Hiard, S., Caruso, A., 2016. Microplastic interactions with freshwater microalgae: hetero-aggregation and changes in plastic density appear strongly dependent on polymer type. Environ. Pollut. 215, 331–339.

Li, H.X., Getzinger, G.J., Ferguson, P.L., Orihuela, B., Zhu, M., Rittschof, D., 2016. Effects of toxic leachate from commercial plastics on larval survival and settlement of the barnacle Amphibalanus amphitrite. Environ. Sci. Technol. 50 (2), 924–931.

Li, L., Zhou, Q., Yin, N., Tu, C., Luo, Y., 2019. Uptake and accumulation of microplastics in an edible plant. Chin. Sci. Bull. 64 (9), 928–934.

Li, L., Luo, Y., Li, R., Zhou, Q., Peijnenburg, W.J.G.M., Yin, N., Yang, J., Tu, C., Zhang, Y., 2020. Effective uptake of submicrometre plastics by crop plants via a crack-entry mode. Nature Sustain. 3 (11), 929–937.

Lian Jiapan, S.M., Weitao, Liu, 2019. Effects of microplastics on wheat seed germination and seedling growth. J. Agro-Environ. Sci. 4, 737–745.

Liao, Y.-C., Nazygul, J., Li, M., Wang, X.-L., Jiang, L.-J., 2019. Effects of microplastics on the growth, physiology, and biochemical characteristics of wheat (Triticum aestivum). Huan jing ke xue= Huanjing kexue 40 (10), 4661–4667.

Liu, X., Li, J., Xue, J., Wu, Fan, Pan, J., 2013. Mechanism of the programmed cell death triggered by plasticizers in the germination process of wheat seeds. J. Triticeae Crop. 2, 350–356.

Liu, Y., Cui, W., Duan, Z., Wang, F., 2019a. Toxicity of polyethylene microplastics to seed germination of mung bean. HUANJINGYUFAZHAN 5, 123–125.

Liu, G., Zhu, Z., Yang, Y., Sun, Y., Yu, F., Ma, J., 2019b. Sorption behavior and mechanism of hydrophilic organic chemicals to virgin and aged microplastics in freshwater and seawater. Environ. Pollut. 246, 26–33.

Liu, P., Lu, K., Li, J., Wu, X., Qian, L., Wang, M., Gao, S., 2020. Effect of aging on adsorption behavior of polystyrene microplastics for pharmaceuticals: adsorption mechanism and role of aging intermediates. J. Hazard. Mater. 384, 121193.

Liu, P., Shi, Y., Wu, X., Wang, H., Huang, H., Guo, X., Gao, S., 2021a. Review of the artificially-accelerated aging technology and ecological risk of microplastics. Sci. Total Environ. 768, 144969.

Liu, P., Wu, X., Huang, H., Wang, H., Shi, Y., Gao, S., 2021b. Simulation of natural aging property of microplastics in Yangtze River water samples via a rooftop exposure protocol. Sci. Total Environ. 785, 147265.

Long, M., Moriceau, B., Gallinari, M., Lambert, C., Huvet, A., Raffray, J., Soudant, P., 2015. Interactions between microplastics and phytoplankton aggregates: Impact on their respective fates. Mar. Chem. 175, 39–46.

Long, M., Paul-Pont, I., Hegaret, H., Moriceau, B., Lambert, C., Huvet, A., Soudant, P., 2017. Interactions between polystyrene microplastics and marine phytoplankton lead to species-specific hetero-aggregation. Environ. Pollut. 228, 454–463.

Lozano, Y.M., Rillig, M.C., 2020. Effects of microplastic fibers and drought on plant communities. Environ. Sci. Technol. 54 (10), 6166–6173.

Lozano, Y.M., Lehnert, T., Linck, L.T., Lehmann, A., Rillig, M.C., 2021. Microplastic shape, polymer type, and concentration affect soil properties and plant biomass. Front. Plant Sci. 12, 14.

Lu, L.L., Tian, S.K., Yang, X.E., Wang, X.C., Brown, P., Li, T.Q., He, Z.L., 2008. Enhanced root-to-shoot translocation of cadmium in the hyperaccumulating ecotype of Sedum alfredii. J. Exp. Bot. 59 (11), 3203–3213.

Ma, X., Geisler-Lee, J., Deng, Y., Kolmakov, A., 2010. Interactions between engineered nanoparticles (ENPs) and plants: phytotoxicity, uptake and accumulation. Sci. Total Environ. 408 (16), 3053–3061.

Ma, S., Zhou, K., Yang, K., Lin, D., 2015. Heteroagglomeration of oxide nanoparticles with algal cells: effects of particle type, ionic strength and pH. Environ. Sci. Technol. 49 (2), 932–939.

Mato, Y., Takada, H., Kanehiro, H., Ohtake, C., Kaminuma, T., 2001. Plastic resin pellets as a transport medium for toxic chemicals in the marine environment. Environ. Sci. Technol. 35, 318–324.

Muller, A., Becker, R., Dorgerloh, U., Simon, F.G., Braun, U., 2018. The effect of polymer aging on the uptake of fuel aromatics and ethers by microplastics. Environ. Pollut. 240, 639–646.

Nel, A.E., Madler, L., Velegol, D., Xia, T., Hoek, E.M., Somasundaran, P., Klaessig, F., Castranova, V., Thompson, M., 2009. Understanding biophysicochemical interactions at the nano-bio interface. Nat. Mater. 8 (7), 543–557.

Ng, E.-L., Huerta Lwanga, E., Eldridge, S.M., Johnston, P., Hu, H.-W., Geissen, V., Chen, D., 2018. An overview of microplastic and nanoplastic pollution in agroecosystems. Sci. Total Environ. 627, 1377–1388.

Nolte, T.M., Hartmann, N.B., Kleijn, J.M., Garnaes, J., van de Meent, D., Jan Hendriks, A., Baun, A., 2017. The toxicity of plastic nanoparticles to green algae as influenced by surface modification, medium hardness and cellular adsorption. Aquat. Toxicol. 183, 11–20.

Pflugmacher, S., Sulek, A., Mader, H., Heo, J., Noh, J.H., Penttinen, O.-P., Kim, Y., Kim, S., Esterhuizen, M., 2020. The influence of new and artificial aged microplastic and leachates on the germination of Lepidium sativum L. Plants 9 (3).

Pignattelli, S., Broccoli, A., Renzi, M., 2020. Physiological responses of garden cress (L. sativum) to different types of microplastics. Sci. Total Environ. 727 (138609).

Priyanka Bhattacharya, S.L., Turner, James P., Chun, Pu, 2010. Physical adsorption of charged plastic nanoparticles affects algal photosynthesis. J. Phys. Chem. C 114 (39), 16556–16561.
Prokin, A.A., Dubov, P.G., Bolotov, S.E., 2015. Formation of macroinvertebrates communities in duckweed (Lemnaceae) and artificial surface-floating substrate: results of the experiment under natural conditions. Inland Water Biol. 8 (4), 373–383.
Qi, Y., Yang, X., Pelaez, A.M., Huerta Lwanga, E., Beriot, N., Gertsen, H., Garbeva, P., Geissen, V., 2018. Macro- and micro- plastics in soil-plant system: effects of plastic mulch film residues on wheat (Triticum aestivum) growth. Sci. Total Environ. 645, 1048–1056.
Qi, Y., Ossowicki, A., Yang, X., Huerta Lwanga, E., Dini-Andreote, F., Geissen, V., Garbeva, P., 2020. Effects of plastic mulch film residues on wheat rhizosphere and soil properties. J. Hazard. Mater. 387, 121711.
Rillig, M.C., de Souza Machado, A.A., Lehmann, A., Klümper, U., 2019. Evolutionary implications of microplastics for soil biota. Environ. Chem. 16 (1).
Ryan, P.G., Moore, C.J., van Franeker, J.A., Moloney, C.L., 2009. Monitoring the abundance of plastic debris in the marine environment. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 364 (1526), 1999–2012.
Salt, David E., R., C.P., Pickering, Ingrid J., Raskin, Ilya, 1995. Mechanisms of cadmium mobility and accumulation in Indian mustard. Plant Physiol. 109 (4), 1427–1433.
Schwab, F., Bucheli, T.D., Lukhele, L.P., Magrez, A., Nowack, B., Sigg, L., Knauer, K., 2011. Are carbon nanotube effects on green algae caused by shading and agglomeration? Environ. Sci. Technol. 45 (14), 6136–6144.
Shiu, R.F., Vazquez, C.I., Chiang, C.Y., Chiu, M.H., Chen, C.S., Ni, C.W., Gong, G.C., Quigg, A., Santschi, P.H., Chin, W.C., 2020. Nano- and microplastics trigger secretion of protein-rich extracellular polymeric substances from phytoplankton. Sci. Total Environ. 748, 141469.
Sjollema, S.B., Redondo-Hasselerharm, P., Leslie, H.A., Kraak, M.H.S., Vethaak, A.D., 2016. Do plastic particles affect microalgal photosynthesis and growth? Aquat. Toxicol. 170, 259–261.
Suhrhoff, T.J., Scholz-Bottcher, B.M., 2016. Qualitative impact of salinity, UV radiation and turbulence on leaching of organic plastic additives from four common plastics - a lab experiment. Mar. Pollut. Bull. 102 (1), 84–94.
Teuten, E.L., S., J.R., Galloway, T.S., Thompson, R.C., 2007. Potential for plastics to transport hydrophobic contaminants. Environ. Sci. Technol. 41, 7759–7764.
Teuten, E.L., Saquing, J.M., Knappe, D.R., Barlaz, M.A., Jonsson, S., Bjorn, A., Rowland, S.J., Thompson, R.C., Galloway, T.S., Yamashita, R., Ochi, D., Watanuki, Y., Moore, C., Viet, P.H., Tana, T.S., Prudente, M., Boonyatumanond, R., Zakaria, M.P., Akkhavong, K., Ogata, Y., Hirai, H., Iwasa, S., Mizukawa, K., Hagino, Y., Imamura, A., Saha, M., Takada, H., 2009. Transport and release of chemicals from plastics to the environment and to wildlife. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 364 (1526), 2027–2045.
Thompson, K.L.L.R.C., 2014. Microplastics in the seas. Science 345 (6193), 144–145.
Tripathi, D.K., Shweta, Singh, Singh, S., Pandey, R., Singh, V.P., Sharma, N.C., Prasad, S.M., Dubey, N.K., Chauhan, D.K., 2017. An overview on manufactured nanoparticles in plants: uptake, translocation, accumulation and phytotoxicity. Plant Physiol. Biochem. 110, 2–12.
Urbina, M.A., Correa, F., Aburto, F., Ferrio, J.P., 2020. Adsorption of polyethylene microbeads and physiological effects on hydroponic maize. Sci. Total Environ. 741, 140216.
van Weert, S., Redondo-Hasselerharm, P.E., Diepens, N.J., Koelmans, A.A., 2019. Effects of nanoplastics and microplastics on the growth of sediment-rooted macrophytes. Sci. Total Environ. 654, 1040–1047.
Velzeboer, I., Kwadijk, C.J., Koelmans, A.A., 2014. Strong sorption of PCBs to nanoplastics, microplastics, carbon nanotubes, and fullerenes. Environ. Sci. Technol. 48 (9), 4869–4876.
Wan, Y., Wu, C., Xue, Q., Hui, X., 2019. Effects of plastic contamination on water evaporation and desiccation cracking in soil. Sci. Total Environ. 654, 576–582.
Wang, H., Wu, Y., Feng, M., Tu, W., Xiao, T., Xiong, T., Ang, H., Yuan, X., Chew, J.W., 2018. Visible-light-driven removal of tetracycline antibiotics and reclamation of hydrogen energy from natural water matrices and wastewater by polymeric carbon nitride foam. Water Res. 144, 215–225.
Wang, F., Zhang, X., Zhang, S., Zhang, S., Sun, Y., 2020. Interactions of microplastics and cadmium on plant growth and arbuscular mycorrhizal fungal communities in an agricultural soil. Chemosphere 254, 126791.
Wathsala, R., Franzellitti, S., Scaglione, M., Fabbri, E., 2018. Styrene impairs normal embryo development in the Mediterranean mussel (Mytilus galloprovincialis). Aquat. Toxicol. 201, 58–65.
Weber, A., Scherer, C., Brennholt, N., Reifferscheid, G., Wagner, M., 2018. PET microplastics do not negatively affect the survival, development, metabolism and feeding activity of the freshwater invertebrate Gammarus pulex. Environ. Pollut. 234, 181–189.
Wu, X., Liu, Y., Yin, S., Xiao, K., Xiong, Q., Bian, S., Liang, S., Hou, H., Hu, J., Yang, J., 2020. Metabolomics revealing the response of rice (Oryza sativa L.) exposed to polystyrene microplastics. Environ. Pollut. 266 (Pt 1), 115159.
Xia, B., Chen, B., Sun, X., Qu, K., Ma, F., Du, M., 2015. Interaction of TiO2 nanoparticles with the marine microalga Nitzschia closterium: growth inhibition, oxidative stress and internalization. Sci. Total Environ. 508, 525–533.
Xu, B., Liu, F., Cryder, Z., Huang, D., Lu, Z., He, Y., Wang, H., Lu, Z., Brookes, P.C., Tang, C., Gan, J., Xu, J., 2019. Microplastics in the soil environment: occurrence, risks, interactions and fate – a review. Crit. Rev. Environ. Sci. Technol. 50 (21), 2175–2222.
Yu, H., Zhang, X., Hu, J., Peng, J., Qu, J., 2020. Ecotoxicity of polystyrene microplastics to submerged carnivorous Utricularia vulgaris plants in freshwater ecosystems. Environ. Pollut. 265 (Pt A), 114830.
Zhang, C., Chen, X., Wang, J., Tan, L., 2017. Toxic effects of microplastic on marine microalgae Skeletonema costatum: interactions between microplastic and algae. Environ. Pollut. 220 (Pt B), 1282–1288.
Zhang, H., Wang, J., Zhou, B., Zhou, Y., Dai, Z., Zhou, Q., Chriestie, P., Luo, Y., 2018. Enhanced adsorption of oxytetracycline to weathered microplastic polystyrene: kinetics, isotherms and influencing factors. Environ. Pollut. 243 (Pt B), 1550–1557.
Zhang, L., Xie, Y., Liu, J., Zhong, S., Qian, Y., Gao, P., 2020. An overlooked entry pathway of microplastics into agricultural soils from application of sludge-based fertilizers. Environ. Sci. Technol. 54 (7), 4248–4255.
Zhang, L., Liu, J., Xie, Y., Zhong, S., Gao, P., 2021a. Occurrence and removal of microplastics from wastewater treatment plants in a typical tourist city in China. J. Clean. Prod. 291, 125968.
Zhang, L., Xie, Y., Zhong, S., Liu, J., Qin, Y., Gao, P., 2021b. Microplastics in freshwater and wild fishes from Lijiang River in Guangxi, Southwest China. Sci. Total Environ. 755 (Pt 1), 142428.
Ziajahromi, S., Kumar, A., Neale, P.A., Leusch, F.D.L., 2018. Environmentally relevant concentrations of polyethylene microplastics negatively impact the survival, growth and emergence of sediment-dwelling invertebrates. Environ. Pollut. 236, 425–431.