

# Chapter 11

## Micro- and Nanoplastics on Plant Functionalities



A. Srividya, Adityah Ganesh, and D. Rathnaprabha

**Abstract** Plastic pollution has become a major environmental concern of the globe. The increasing plastic pollution has captured the attention of many researchers. Disposal of plastic on land and in water, in due course, leads to the production of various plastic particles like micro (1–5 mm) and nano (1–100 nm) plastics by diverse physico-chemical processes. These micro- and nanoplastics are ubiquitous and have become the major contributors of pollution to aquatic and terrestrial ecosystems. Plants, which are considered as the main producers of the terrestrial and aquatic ecosystems, are vulnerable to the plastic pollutants. Terrestrial and aquatic plants are exposed to different types of plastics, leading to altered physiological and metabolic functions. This chapter has highlighted the impact of micro- and nanoplastics on plants during seed germination and growth. The altered responses of plants are because of the imbalances in soil microbial community, anti-oxidative enzymes and photosynthetic and metabolic activities. Various characteristics of autotrophic macrophytes on exposure to plastic pollutants are also being focussed on. Many of these studies have shown the inhibitory effects of these particles, which are dependent on their size, shape, charge and concentration used. Based on the size, they get adsorbed or internalised by the plant, which reduces its growth and photosynthetic activity primarily by inducing oxidative stress. The accumulated particles block the pores on the seed and root surface thereby affecting seed germination and also nutrient uptake by roots. This chapter covers the major research topics that investigated the effects of micro- and nanoplastics on various parameters of plant growth and functions. The effects of micro- and nanoplastics on plant functionalities are being discussed.

**Keywords** Microplastics · Nanoplastics · Functionalities · Polyethylene · High-density polyethylene · Low-density polyethylene · Polystyrene · Oxidative stress

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## 11.1 Introduction

We live in a world surrounded by plastic. Usage of plastic has become convenient as it is economical and reliable (Boucher & Friot, 2017). The usage of plastic has increased by 25 folds over last 40 years (Sutherland et al., 2014). Because of its extensive and uncontrollable use, plastic pollution has become a global issue. Plastic production was estimated to be more than 359 million tons as of 2019 (Europe, 2017). The estimated plastic production would reach 12,000 million tons by 2050 (Geyer et al., 2017). In spite of recycle and reuse, 32% of the plastic waste still remains in the natural habitat (Geyer et al., 2017; de Souza Machado et al., 2018).

Plastic contamination is omnipresent, on land and in water, namely, oceans, lakes, estuaries and shores (Alomar et al., 2016; Browne et al., 2011; Naidoo et al., 2015). Plastic gets degraded in course of time by physical and biological processes. Plastic particles that are synthesised primarily for certain purposes and those that originated from degradative process will eventually lead to marine water with runoff, which is the main source of plastic in marine water (Andrady, 2011). So, most of the focus was on marine plastic pollution but terrestrial environment is also a major recipient of plastic pollutants (Khalid et al., 2020; Zhou et al., 2021). Plastic pollution generates particles of various sizes, ranging from micro to nano size in course of time.

Soil is the source of many plastic particles in terrestrial ecosystem, which hints us of the safety of agricultural crops and food. Soil polluted with various plastic particles like micro and nanoplastics will affect plants negatively or positively (de Souza Machado et al., 2018). Micro and nanoplastic pollution is widespread. Microplastics (MPs) are found in various terrestrial systems like agricultural fields and industrial areas (Piehl et al., 2018; Fuller & Gautam, 2016). Microplastics are becoming a threat to terrestrial ecosystem (de souza Machado et al., 2018). They alter the soil structure and plant performance (de souza Machado et al., 2019). They change the physical and chemical properties of the soil and affect microbial activities and plant performance (Xu et al., 2020). These effects are dependent on their shape and size rather than on their chemical composition (Rillig & Lehmann, 2020). Khalid et al. (2020), have described various direct and indirect ways of microplastic effects on terrestrial plants. Microplastics show direct effects on plant growth and functionalities; and indirectly affect plants by altering soil properties and soil-microbe interactions. Zhou et al. (2021) have focussed on the effects of microplastics on soil properties and microbial communities. Microplastics are found to alter soil properties like aggregation (Rillig et al., 2017) and soil pH (Boots et al., 2019). Because of the altered properties, plant performance would be affected.

Various kinds of microplastics have shown variable effects on plant growth, as noticed in *Triticum aestivum*, *Allium fistulosum*, *Lactuca sativa* and *Phaseolus vulgaris*, under different conditions (de Souza Machado et al., 2019; Jiang et al., 2019; Meng et al., 2021; Qi et al., 2018).

Nanoparticles are inherently difficult to detect and analyse as the minimum size limits of most of the commonly used sampling and analysis techniques fall in the

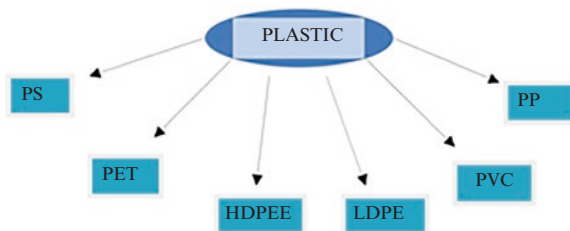
range of 10–100  $\mu\text{m}$  (Li et al., 2020c, 2021a; vanWeert et al., 2019). This creates the additional challenge of detecting and tracing nanoplastics in human food items and animal feeds. The nanoplastics should therefore be evaluated for presence in food production chain, mode of entry of the plastic into the production chain, and effect of the particles on production process and potential risks that may develop from it (Yin et al., 2021; Mateos-Cárdenas et al., 2021). Various effects of MPs and NPs on agro-ecosystems were reported by Ng et al. (2018). As plants are primary producers and main living constituents of the environment, much attention is needed to understand the effects of micro plastics (MPs) and nanoplastics (NPs) on them.

## 11.2 Types of Plastics

There are various classes of plastic depending on their physicochemical properties, namely, polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), Polystyrene (PS), polypropylene (PP), polyvinyl chloride (PVC) and others (Fig. 11.1). These are produced to a great extent and commonly found in the environment. Plastic span over different shapes and sizes, Microplastics (MPs) are those plastic particles ranging from 1 to 5 mm (Frias & Nash, 2019) and particles ranging from 1 to 100 nm that exhibit colloidal behaviour are Nanoplastics (NP) (Gigault et al., 2018). Because of their extensive usage, plastic particles are widespread across the world. They have many effects on living beings, including human beings.

Different types of MPs have been detected in the environment (Mintenig et al., 2019; Sharma & Chatterjee, 2017) these plastic particles cause serious environmental problems. Primary microplastics are those that are synthesised for some purposes like fabrication, as cosmetics and in the form of microbeads. Secondary microplastics emerge from the fragmentation of larger plastics by physical, chemical and biological processes (Duis & Coors, 2016; De Falco et al., 2019). These microplastics are of various shapes, like beads, fibres, films and fragments, which are carriers of various toxic substances (Wang et al., 2018). Depending on their shape, they show various effects on plants, directly or indirectly (Rillig et al., 2019).

Fig. 11.1 Types of plastics



### 11.2.1 Sources of MPs and NPs

Microplastics/Nanoplastics enter into plants from the soil, which acts as the medium of transfer. An ample focus was drawn to microplastics pollution because of the reports that stated much of microplastics that were released were from personal care products (Duis & Coors, 2016). Soil polluted with microplastics will affect plant performance (de Souza Machado et al., 2019). Main sources of microplastics in soil arise from municipal sludge, irrigation water and plastic mulching. Plastic used in agriculture (agroplastic), is considered to be an important source of plastic in terrestrial ecosystem, whose usage is expected to increase 69% from 2012 to 2019 (Sintim & Flury, 2017). Wastewater treatment plants remove waste from water and prevent them from entering water sources. The remaining sludge is used as fertiliser in agricultural fields, which is the main source of plastic particles in agricultural fields (Alimi et al., 2018; Hurley & Nizzetto, 2018). Corradini et al. (2019) have emphasised on the role of municipal sludge in contaminating agricultural soil with plastic particles. While wastewater treatment methods can remove up to 90% of the micro and nanoplastics that exist in the wastewater, this amount is not satisfactory and the use of this treated water in agriculture for irrigation has effectively introduced micro and nanoplastic from the water into the agricultural ecosystem (Fig. 11.2).

Increasing microplastics are an alarm to indicate the threat imposed on environment. Leaching of plasticisers and polymers from municipal waste disposal sites into ground water impose threat to terrestrial ecosystem (Teuten et al., 2009). Huang et al. (2020) have described plastic mulching as the source of microplastics in the soil. They are also commonly found in the aquatic ecosystem like oceans, lakes and

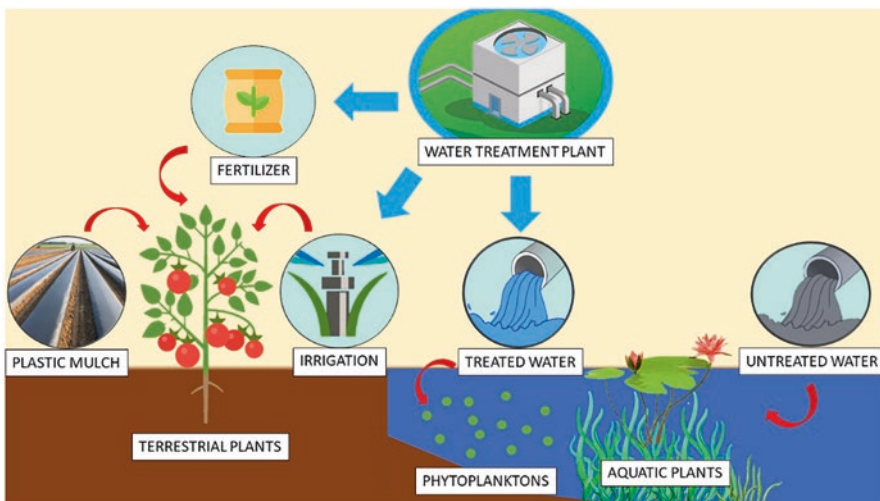


Fig. 11.2 Sources of micro and nanoplastics to terrestrial and aquatic plants

estuaries, which have been accumulating over last four decades (Thompson et al., 2004). Runoff and weathering are the main sources of microplastics in marine waters (Andrady, 2011).

There are various sources, through which NPs enter the terrestrial environment. Nanoplastic sources can be broadly classified as point sources and non-point sources. Point sources include sources from which free nanoparticles are directly dispersed into the surrounding environment. This includes direct release of nanoplastics into the environment as a result of untreated release and undesired leakage or spill out during the production and transport of nanoplastics; and products that use micro and nanoplastics (Yano et al., 2021). The advancing trend in the consumer industry (Yoshino et al., 2012) to lean towards nanoparticles has resulted in the production of nano particulate polymers which can add to the pool of nanoplastic in the environment thus acting as non-point sources of nanoplastic pollution into the environment.

### ***11.2.2 Accumulation of MPs and NPs in Plants***

MPs and NPs can adsorb on the surface of the plants and enter into plant system. Some of these particles are usually trapped on the root surface and enter root cells (Li et al., 2019). Various fluorescently labelled tags were used to track their transport, NPs and micro-sized MPs were found to travel from root to leaf (Li et al., 2020a, b). They travel to the upper parts of the plant by transpirational pull (Li et al., 2020a). Depending on their size and shape, these MPs and NPs can affect plants. They may have a positive or negative effect on plants depending on the species (Rillig et al., 2019). Vascular plant tissues have been observed to adsorb nanoplastics under specific conditions. Studies using scanning electron microscopy (SEM) and laser scanning confocal microscopy (LSCM) have observed the location specificity and internalisation process of nanoplastics in plants (Khalid et al., 2020; Lian et al., 2020; Yan et al., 2021a). These studies have shown that absorption of nanoplastics depends on the plant species and characteristic properties of the plastic.

Positively and negatively charged NPs accumulated differently in *A. thaliana* (Sun et al., 2020). PS beads have been found to accumulate on the root surface but are not absorbed in floating plants like *Spirodela polyrhiza* (Mateos-Cárdenas et al., 2019). MPs were detected on seagrass and macroalgae by Seng et al. (2020), these macrophytes act as glue for various plastic particles and serve as temporary sink for MPs (Sfriso et al., 2021), which hold MPs in aquatic environment. Fibres are more predominant in MPs, retained by filamentous algae (Esiukova et al., 2021). Internalisation of PS microbeads was studied using fluorescently labelled particles. These MPs (80 and 1  $\mu\text{m}$ ) are being absorbed by roots and translocated to the aerial parts through the vascular system in rice. This study highlights the accumulation of MPs in crop plants and their probable transfer in food chain (Liu et al., 2022; Li et al., 2020c). Physical deformations or damages in the plant roots can provide pathways for the entry of plant nanoparticles into the plant. A study conducted by Li

et al. (2020a) revealed that cracks in the lateral roots of lettuce (*Lactuca sativa*) and wheat (*Triticum aestivum*) provided a pathway for the entry of nanoparticles of PMMA (polymethylmethacrylate) and PS (polystyrene). Another pathway that can lead to nanoplastic internalisation is the endocytosis through a liquid phase. Zhou et al. (2021) showed that aquaporins can assist in the nanoplastic intake.

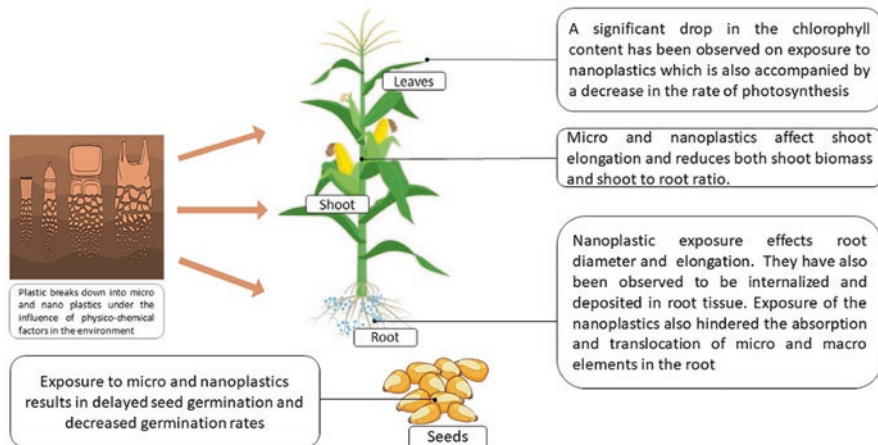
Airborne MPs are gaining attention for being a threat to human health (Cox et al., 2019). Terrestrial plants act as a sink for various particulate matter, including MPs (Rindy et al., 2019). Depending on the leaf trait (leaf area and hairiness), particulate matter is being deposited on the urban trees, which are usually considered to reduce the pollutants in the air (Chiam et al., 2019). So, terrestrial plants act as an important sink for MPs and influence their accumulation in plants and soil (Bi et al., 2020). Airborne transport and accumulation of NPs have also been demonstrated in *Zea mays* L. by Sun et al. (2021). They exposed leaf of *Zea mays* L. seedlings to both positively and negatively charged PS particles. Positively charged PS particles aggregation was more notable and travelled from leaf to the roots through vascular bundle, which induced inhibitory effect on photosynthesis. MPs in combination with other chemical compounds have more adverse effects on plants (Prata et al., 2018). MPs/NPs in the soil serve as reservoirs of many pollutants. Cyanotoxins (CTX) released by bacteria would accumulate on MPs/NPs and serve as co-contaminants. Maity et al. (2021) have presumed the importance of these co-contaminants as phytotoxic. MPs, especially the abundant polystyrene (PS) was found to be accumulated in plants using fluorescent dyes by confocal laser scanning microscope (Li et al., 2020b). These MPs and NPs accumulate in plants by various ways and pose health risks to humans. A study on risk assessment of MPs on edible fruits and vegetables was carried out by Conti et al. (2020). Apple and carrot are the most contaminated fruit and vegetable respectively. There are various studies that concentrated on effects of MPs and NPs on plant performance, like seed germination, photosynthesis, growth and others. The present chapter explains the effect of these MPs/NPs on plant functionalities.

### 11.3 Effects of MPs and NPs on Plant Functionalities

MPs/NPs affect plants negatively, by reducing growth and photosynthetic activity in terrestrial and aquatic primary producers. Majority of MPs/NPs induce oxidative stress, thereby increasing anti-oxidative enzyme levels. Various effects of MPs/NPs include inhibition of seed germination, reduced or inhibited photosynthetic activity, reduction of root and shoot lengths, plant biomass and others (Fig. 11.3). The direct and indirect effects of MPs/NPs on plants based on the published literature are discussed below:

#### (i) *Effects of MPs and NPs on Seed Germination:*

MPs and NPs have shown to affect seed germination in various plant species. These effects are dependent on their size and concentration (De Silva et al., 2021)



**Fig. 11.3** Effects of micro and nanoplastics on various plant functionalities based on the organ they accumulated

as shown in Table 11.1. Soil is the main sink for these particles. MPs (PLA, polylactic acid) accumulated in soil and affected germination in *L. perenne* (Boots et al., 2019). Many of the studies report that MPs adsorb on the plant surface, whereas NPs are being absorbed into the plants. The accumulated particles on the seed surface reduce the germination rate (De Silva et al., 2021). Recent studies have highlighted that seed germination and growth of plants are dependent on the age of decaying plastic. Based on the age of microplastic, its toxicity also varied on the germination, growth and photosynthesis in *L. Sativum* (Pflugmacher et al., 2021). Bosker et al. (2019) studied the effects of differently sized MPs (50, 500 and 4800 nm) of different concentrations on seed germination of *L. sativum*, using 72 h germination assay. Germination was reduced due to the blockage of the seed capsule by accumulated MPs. The impact of PS-MPs (2  $\mu\text{m}$  and 80 nm) on germination of ornamental plants was studied by Guo et al. (2022). It was found that these MPs could inhibit germination in these species depending on their concentration (Table 11.1). Zhang et al. (2021b) studied the effect of PS-MPs (200 nm) on the seed germination of rice. These particles showed no significant effect on seed germination but reduced the activity of anti-oxidative enzymes. Reactive oxygen species (ROS) levels increased in roots and transcriptome analysis revealed that PS-MPs increased the activity of anti-oxidative enzymes in roots.

The composition of MPs also affects the toxicity. Various MPs like PP, PE and PVC were analysed on different growth parameters like seed germination, plant height, biomass production and oxidative stress levels in *Lepidium sativum*, by Pignattelli et al. (2020). The evaluated toxicity was found to be due to PVC on *L. Sativum*. These particles alone or in combination with other toxic elements will affect the plant performance, as witnessed in *L. sativum*. PET alone or with acid rain was found to negatively affect seed germination, plant growth and increased chl<sub>b</sub> production (Pignattelli et al., 2021). Ethylene vinyl acetate (EVA), LLDPE (Linear

**Table 11.1** Effects of MPs/NPs on seed germination of various plant species

Plant	MP/NP type	Size	Effect on seed germination	Reference
<i>L. perenne</i>	Poly lactic acid HDPE	Mean diameter: HDPE: 102.6 µm PLA: 65.6 µm	Germination reduced reduction in shoot length HDPE: decreased soil pH	Boots et al. (2019)
<i>L. sativum</i>	MPs	50, 500 and 4800 nm	Decreased germination rate	Bosker et al. (2019)
<i>L. sativum</i>	PP, PE, PVC	Not mentioned	Oxidative burst induced decreased germination	Pignattelli et al. (2020)
<i>L. sativum</i>	PET, acid rain	60–3000 µm	Reduced germination induced oxidative burst	Pignattelli et al. (2021)
<i>T. aestivum</i>	EVA, LLDPE, PMMA	Not mentioned	Inhibited seed germination	Lian et al. (2019)
Italian lettuce	PSNPs and micro PS	Not mentioned	Germination inhibited	Gong et al. (2021)
Rice	PS-MPs	200 nm	No significant effect increase in length and ROS in roots	Zhang et al. (2021b)
<i>Trifolium ripens</i> , <i>O. violaceus</i> , <i>Impatiens balsamina</i>	PS-MP	2 µm and 80 nm	Inhibited germination rates	Guo et al. (2022)

MP Microplastic, PSMP Polystyrene microplastic, PSNP Polystyrene nanoparticle, PP Polypropylene, PE Polyethylene, PVC Polyvinyl chloride, PET Poly ethylene terephthalate, PSNP Polystyrene nanoplastic, EVA Ethylene vinyl acetate, LLDPE Linear low density poly ethylene, HDPE High density polyethylene, PMMA Poly methyl methacrylate, ROS Reactive oxygen species

low-density polyethylene) and poly methyl methacrylate (PMMA) have shown to inhibit seed germination in *Triticum aestivum*, at lower concentrations (Lian et al., 2019). MPs derived from fertilisers have exhibited differential effects on wheat growth and soil properties (Lian et al., 2021b).

A systemic study done on the effect of polystyrene nanoplastics (PSNPs) on crop plant *Triticum aestivum* L. (Lian et al., 2020) and on *Allium cepa* (Giorgetti et al., 2020), has shown that PSNPs exhibited no visible effect on seed germination. But there was an increase in root length and decrease in shoot-to-root biomass ratio in *T.aestivum*. PSNPs' effect on seed germination is species dependent. Among the four food crops (Italian lettuce, radish, wheat and corn) exposed to PSNPs and microspheres (micro PS), seed germination in Italian lettuce was inhibited at a very early stage of development. It was also observed that these toxic effects are because of the oxidative stress imposed on plants (Gong et al., 2021). A pot experiment conducted by Li et al. (2021a) on effects of LDPE and bio mulch on germination and growth of *Glycine max* has shown that bio-mulch has negatively affected germination viability and LDPE affected plant height.



(ii) *Effects of Accumulated MPs and NPs on Plant Growth:*

MPs and NPs, when accumulated in plants, affect their growth directly in various ways, like reduction in biomass and by induction of oxidative stress. These plastic pollutants are ubiquitous; they are toxic alone or in combination with other organic or metallic pollutants. They even affect plant performance indirectly by altering soil properties like soil pH or soil microbial community (Rillig et al., 2019). Foliar application of PSNPs have shown to reduce the growth and induce oxidative stress in lettuce. These NPs got absorbed at the leaf and transported to the root part. They reduced nutritional quality, biomass and leaf size of lettuce (Lian et al., 2021a).

(a) *Direct Effects of MPs and NPs on Plant Growth:*

Much of the scientific attention is being driven by these pollutants and their effects on agricultural crops, which were studied using hydroponic cultures in certain crop plants. Accumulation of MPs (PE microbeads) in the rhizosphere and reduction in water and nutrient uptake were observed in hydroponic maize. Upward transport of PE beads to shoot was not observed (Urbina et al., 2020). In hydroponic wheat seedlings, there was no effect of PSMPs on photosynthesis and oxidative stress. Instead, PSMPs reduced the toxicity of cadmium and copper on wheat seedlings (Zong et al., 2021). Rice (*Oryza sativa*) seedlings were exposed to 1  $\mu\text{m}$  and 100 nm PSMPs, to study their toxic effects in hydroponic conditions. 1  $\mu\text{m}$  PS were more toxic than 100 nm particles in rice seedlings (Wu et al., 2021). Differently sized particles would affect plants differently. MPs of 1  $\mu\text{m}$  size accumulated in the intercellular space of carrot roots. But larger MPs would enter roots and leaves in the presence of arsenic. They reduced the quality of carrots and eventually led to health risks (Dong et al., 2021b).

Molecular and physiological effects of differently sized MPs were studied in maize seedlings by Pehlivan and Gedik (2021). They analysed various combinations of MPs differing in their sizes, for their toxicity. They induced xenobiotic stress in the maize. It was observed that the bigger the particle size, the quicker they restore to the normal condition. Their research insists on the toxicity of pollutants on agricultural crops. Likewise, the toxicity of MPs on the leguminous plant soybean was also investigated by Xu et al. (2021). PSMPs decreased the availability of organic pollutants like phenanthrene in soybean seedlings. It was shown that PSMPs along with phenanthrene are harmful to higher plants. Ren et al. (2021) studied the effect of PS beads on the growth of Chinese cabbage. They found that these plastic particles have soil-microbial community that would affect the plant growth.

Nanoplastics can get internalised in plants and affect them adversely. Exposure of corn to PSNPs has altered the plant's metabolic rates because of the elevated anti-oxidative enzymes. But photosynthetic activity was not altered (Zhang et al., 2021a). The effect of PSNPs was also studied in cucumber by exposing it to different sized particles. It was found that they first accumulated at root but later transported to fruit, flower and leaves. They increased the protein content of fruit and also root activity (Li et al., 2021b). Differently charged nanoplastics accumulated differentially in *Arabidopsis thaliana*. Positively charged particles, though accumulated

slowly, could reduce the growth of the plant. Negatively charged particles were found in apoplast and xylem (Sun et al., 2020). Giorgetti et al. (2020) studied the interaction of PSNPs and *Allium cepa*. Various concentrations of PSNPs (0.01, 0.1 and 1 mg/L) were used during germination. All concentrations were shown to inhibit root length. Higher concentrations were found to induce oxidative stress. The internalisation and movement of particles was visualised using TEM. Internalised nanoplastic particles in food crops raise concerns for food safety, as they are transferred in trophic levels. Foliar application of positively and negatively charged PSNPs on *Zeamays L.* was carried out to observe the absorption tendency of air transported NPs carrying different charges. They got internalised and transported to the root leading to photosynthesis inhibition by PS-NH<sub>2</sub> (Sun et al., 2021).

In higher plants like *Vicia faba*, the root tips were exposed to 5 and 100 nm PSMPs of various concentrations. It was observed that 100-nm particles accumulated in roots and blocked intercellular connections. There was a decrease in the growth with 100-nm particles, which have also proven to be genotoxic and imposed oxidative damage (Jiang et al., 2019). In lettuce, MP (PS) under di-n-butyl phthalate (DBP) stress conditions induced toxicity by blocking root pores. PS in lettuce decreased biomass by inducing oxidative stress and damaging leaves and root. (Gao et al., 2021a). Similar research was carried to study the effect of PS and DBP on green and purple lettuce. Toxicity induced was dependent on the variety; purple variety was more sensitive to PS. The toxicity induced was by reducing growth of root, soluble protein and sugar in leaves (Gao et al., 2021b). PE MPs effect on cadmium (Cd) bioavailability was also investigated in lettuce by Wang et al. (2021). They increased the availability of Cd and accumulation in plants. This study suggests that MPs increase the toxicity of heavy metals in contaminated soils. Toxicological effects of MPs on farmland were researched on crops like lettuce. Physiological responses of lettuce in presence of PVC microplastics were studied by applying different sizes of PVC (100 nm–18 µm and 18–150 µm). Various contents were analysed on the root activity, which had no effect. But, root length, diameter and surface were increased. Photosynthetic activity was altered with 100 nm–18 µm particles and 18–150 µm sized particles were correlated to root morphology (Li et al., 2020b).

(b) *Indirect Effects of MPs on Plants:*

Microplastics show altered effects on various plants indirectly by changing soil structure, properties or soil microbial interaction. Boots et al. (2019) have reported the change in soil structure in the presence of HDPE and PLA, which results in altered soil ecosystem. Different MPs show different effects on soil property and plant biomass, based on their concentration (Lozano et al., 2021). These altered structure and physicochemical properties of soil will affect the plant functionalities. de souza Machado et al. (2019) conducted an experiment to study the effects of six different MPs on *Allium fistulosum*. Depending on the type and size, they altered the soil properties, which affected the plant's performance. MPs get integrated into the soil when they reach the soil surface (Rillig et al., 2017). They contain a lot of organic carbon, so they add to the organic part of the soil, which will affect the

carbon cycle in the soil and the plant's performance (Rillig et al., 2021). Hydroponic cultures of maize were employed to study the effect of MPs. Isotopic analysis was used to study the effects of MPs and it was noticed that 30% of the carbon in the rhizosphere was derived from microplastic (Urbina et al., 2020). Biodegradable plastic is being employed in the place of plastic mulching, which releases various compounds on degradation. An in vitro toxicity test was conducted to study the effects of biodegradable plastic on crop plants. Among the compounds released from bioplastic, adipic acid was shown to inhibit growth of tomato and lettuce (Martin-Closas et al., 2014). The influence of biodegradable plastics on soil microbial communities and agro-ecosystem was reported by Bandopadhyay et al. (2018).

(iii) *Effects of MPs on Plant Community:*

The effects of microplastics are mainly dealt with in an individual or in plant species. But the effects of microplastics vary with plant species within a community. MPs have been found to show allelopathic effects, which affect plant community structure. In allelopathy, they promote the growth of same species and inhibit the same of neighbour. Lozano and Rillig (2020) have demonstrated this in *Hieracium* and its neighbour *Festuca*. They affect the community structure and plant productivity (Rillig et al., 2019), which is witnessed in root length of *Plantago lanceolata* (forb) and *A. fistulosum*. They have shown opposite responses to microplastic exposure (de Souza machado et al., 2019; Van Kleunen et al., 2020). So, this indicates that microplastics affect varyingly on different plant species within a community. Yu et al. (2021b), highlighted the importance of research on the effects of microplastics on plant biomass and community structure. Lozano and Rillig (2020) have shown the effect of microfibrils on productivity and structure of plant community. They witnessed the dominance of an allelopathic species in the presence of microplastics and reduced biomass of the other species in a community.

(iv) *Effects of MPs and NPs on Growth of Aquatic Photosynthetic Organisms:*

The aquatic system receives much of plastic particles by runoff. They adversely affect many aquatic plants in various ways. The toxicity exhibited by these plastic particles is dependent on their properties like charge, type and size (Lagarde et al., 2016). Charge dependent toxicity was witnessed in microalgae, *Dunaliella tertiolecta*. Positively charged nano-PS particles have inhibited the growth when compared to negatively charged PS particles (Bergami et al., 2017). Schiavo et al. (2021) found the toxic effects of PS, PP and PE leachates on growth and DNA of microalgae. As the macrophytes exposed to various concentrations of MPs and NPs, NPs were found to be more effective in reducing shoot to root length compared to MPs (vanWeert et al., 2019). In a comparative study of the effects of MPs and NPs, PSNPs were found to impose a more inhibitory effect on the growth of *Chlamydomonas reinhardtii*. The treated algal species was shown to have increased levels of reactive oxygen species and malonaldehyde. Internalised NPs were visualised in vacuoles. They mainly imposed oxidative stress in the algae (Yan et al., 2021b). Yang et al. (2020) proved the toxic effects of MPs (PS, PE, PA) on growth due to oxidative stress in *Chlorella pyrenoidosa*. Similar effect of PSMPs was

observed on the growth of *Chlorella pyrenoidosa*; there was reduction in the growth due to oxidative stress and physical damage. Later, it could regain its growth in late logarithmic phase (Mao et al., 2018). In the floating plant *Salvinia cucullata*, the combined effect of MPs and herbicide (glyphosate) has reduced the growth by activating antioxidative enzymes. PSMP (1  $\mu\text{m}$ ) could reduce relative growth and root morphology. These findings indicate the toxic effects of contaminants in aquatic ecosystems (Yu et al., 2021a). A growth inhibition rate of 39.7% was also observed in marine microalgae *Skeletonema costatum*, on 96 h exposure to MPs. The toxicity was dependent on particle size and concentration of MPs on interaction with microalgae (Zhang et al., 2017). The toxicity of MP in combination with Cu nanoparticles and triclosan was also studied in *Skeletonema costatum* (Zhu et al., 2019; Zhu et al., 2020), shown in Table 11.2. *Chlamydomonas reinhardtii* was also affected by an inhibition rate of 45.8%, on exposure to PSMPs (Li et al., 2020d). Kalčíková et al. (2017) studied the effect of PE microbeads on freshwater duckweed, *Lemna minor*. It was observed that these particles reduced the root length, but the photosynthetic activity was not affected (Table 11.2).

(v) *Effects of MPs and NPs on Photosynthetic Activity of Plants:*

Photosynthetic organisms are present in aquatic and terrestrial systems. They are the primary producers and sinks for  $\text{CO}_2$ . MPs and NPs have shown to affect photosynthesis by altering chlorophyll content in photosynthetic organisms (Table 11.3). Photosynthetic activity was reduced in cucumber plant when it was exposed to various sizes of PSNPs (100, 300, 500 and 700 nm). Among them 100 nm particles reduced chlorophyll-a and chlorophyll-b content, along with fluorescence in leaves. Exposure to 300 nm particles reduced biomass, while 700 nm particles induced oxidative stress in leaves (Li et al., 2020a). An antagonistic response was observed in wheat seedlings on exposure to PSNPs. The photosynthetic activity was increased at 0.1 mg/L concentration and shoot-to-root ratio was decreased at 0.01 mg/L concentration (Lian et al., 2020).

MPs act as carriers of many pollutants and exert their effects on crop plants. Effects of MPs in combination of other pollutants were being investigated in some of the researches. Growth and photosynthetic activity were reduced in lettuce, on exposure to MP (PE) and di-n-butyl phthalate (DBP). Exogenous MP has further increased the effect of DBP on photosynthesis (Gao et al., 2019). The integrated effect of PS and di-butyl phthalate (DBP) on photosynthesis of red lettuce were studied Dong et al. (2021a). It was noted that PS particles reduced the uptake of DBP; jointly, they could reduce photosynthetic activity and also the quality of red lettuce. This explains the possible risk of microplastics on vegetable crops.

(a) *Effects of MPs and NPs on Photosynthesis of Aquatic Photosynthetic Organisms:*

Microalgae are primary producers in the aquatic ecosystem; study of plastic pollutants on these organisms will give us an insight into how MPs/NPs would affect photosynthetic process (Table 11.3). Small size and positive surface charge on MPs will have more adverse effects on microalgae (Prata et al., 2019). Small-sized PSMPs (0.05  $\mu\text{m}$ ) were proven to have adverse effects at certain concentrations, on

**Table 11.2** Effects of MPs/NPs on growth of terrestrial and aquatic photosynthetic organisms

Plant	MP/NP	Size	Effect	Reference
Lettuce	PSNP	Not mentioned	Reduction in biomass, quality and leaf size imposed oxidative stress	Lian et al. (2021b)
Cucumber	PSNPs	100 nm	Decrease in chl <sub>a</sub> , chl <sub>b</sub> in leaves	Li et al. (2020b)
		300 nm	Decrease in biomass	
		500 nm	Altered enzymatic activity	
		700 nm	Increase in anti-oxidative enzymes; induction of oxidative stress	
Cucumber	PSNPs	100, 300, 500, 700 nm	Increase in soluble protein in fruits and increase in root activity, MDA and proline content by 300 nm particles	Li et al. (2021b)
Maize	PE microbeads	Not mentioned	Plastic bioaccumulation in rhizosphere water and nutrient uptake reduced	Urbina et al. (2020)
Maize	PP, PET, PVC, PS, PE (PP + PET + PVC + PS + PE)	75–150 µm 150–212 µm	Decreased photosynthetic pigments oxidative stress	Pehlivan and Gedik (2021)
Maize	HDPE, PLA	Not mentioned	High dose of PLA decreased biomass	Yang et al. (2021)
Carrot	MP	1 µm	Accumulated in roots	Dong et al. (2021a)
		Larger MPs and arsenic	Reduced quality of carrot	
Soybean	PSMP + Phe	1, 10, 100 µm	Oxidative stress decreased activity of root	Xu et al. (2021)
<i>Vicia faba</i>	PSMPs	5, 100 nm	Accumulated in roots and blocked intercellular connections	Jiang et al. (2019)
Lettuce	PSMP + DBP	SPS 100–1000 nm LPS >1000 nm	Blocked root pores leaf and root damage oxidative stress	Gao et al. (2021b)
Wheat	PS + degradable mulching film	5 and 70 nm	Decreased base diameter and microbial community increased plant height	Ren et al. (2021)

(continued)

**Table 11.2** (continued)

Plant	MP/NP	Size	Effect	Reference
Corn	PSNPs	100, 300, 500 nm	Metabolic rate altered anti-oxidative enzymes increased	Zhang et al. (2021a)
<i>Oryza sativa</i>	PSMP	1, 100 nm	Reduced growth oxidative stress	Wu et al. (2021)
<i>Allium cepa</i>	PSNP	50 nm	Reduction in root length at concentrations (0.1 and 1 mg/L) oxidative stress at higher concentrations cytotoxic and genotoxic	Giorgetti et al. (2020)
<i>Allium fistulosum</i>	PE fibres, PA beads, PP, PS, Poly ester terephthalate (PET) and PE	PA: 15–20 $\mu\text{m}$ PE fibres: length 5000 $\mu\text{m}$ ; diameter 8 $\mu\text{m}$ PEHD: 643 $\mu\text{m}$ PET: 376 $\mu\text{m}$ PP: 816 $\mu\text{m}$ PS: 754 $\mu\text{m}$	PA: increase in soil nitrogen content; increase in total biomass increase in onion bulb biomass PE fibres: altered soil biophysical properties, increase in root biomass and decrease in diameter PEHD: decrease in soil bulk density	de Souza Machado et al. (2019)
<i>Arabidopsis thaliana</i>	NP	–	Positively charged reduced the growth internalisation of negatively charged particles	Sun et al. (2020)
<i>Zea mays</i>	PSNP PS-COOH PS-NH <sub>2</sub>	–	PS-NH <sub>2</sub> inhibited photosynthesis	Sun et al. (2021)
<i>Myriophyllum spicatum</i> and <i>Elodea sp</i>	PSNPs	50–190 nm	Reduced shoot to root biomass	vanWeert et al. (2019)
	PSMPs	20–500 $\mu\text{m}$	Increase in shoot length in <i>M. spicatum</i>	
<i>Dunaliella tertiolecta</i>	PS, PP and PE	5 mm $\pm$ 0.3	Growth inhibited, induced oxidative stress DNA damaged	Schiavo et al. (2021)
<i>Chlorella pyrenoidosa</i>	MP (PS, PE, PA)	PE1000, 13 $\mu\text{m}$ and PE150 $\mu\text{m}$ PA1000, 13 $\mu\text{m}$ and PA150 $\mu\text{m}$ PS 150 $\mu\text{m}$	Growth inhibition oxidative stress	Yang et al. (2020)
<i>Lemna minor</i>	PE microbeads	30–600 $\mu\text{m}$	Root length affected viability of root cells decreased with sharp particles	Kalčíková et al. (2017)

(continued)

**Table 11.2** (continued)

Plant	MP/NP	Size	Effect	Reference
<i>Dunaliella tertiolecta</i>	PSNP PS-COOH PS-NH <sub>2</sub>	40 and 50 nm	PS-NH <sub>2</sub> (aggregates of <200 nm) inhibited algal growth	Bergami et al. (2017)
<i>Salvinia cucullata</i>	PSMP	1 µm	PSMP reduced relative growth and root morphology	Yu et al. (2021a)
<i>Skeletonema costatum</i>	mPVC	1 µm	Growth was inhibited at high concentrations photosynthesis was reduced	Zhang et al. (2017)
<i>Skeletonema costatum</i>	MP and TCS	PE, PS, PVC: 74 µm PVC 800: 1 µm	TCS is more inhibitory than other MPS PVC + PVC800 + TCS: toxicity reduced	Zhu et al. (2019)
<i>Skeletonema costatum</i>	mPVC, Cu nano	–	Growth inhibition cell membrane damage mPVC reduced the toxicity of Cu nanoparticles	Zhu et al. (2020)

*PSMP* Polystyrene microplastic, *PSNP* Polystyrene nanoparticle, *PP* Polypropylene, *PE* Polyethylene, *PVC* Polyvinyl chloride, *PET* Poly ethylene terephthalate, *PEHD* Poly ethylene high density, *PSNP* Polystyrene nanoplastic, *PLA* Poly lactic acid, *chl a* chlorophyll a, *TCS* Triclosan, *Phe* Phenanthrene

microalgae by inhibiting growth, but photosynthesis was not affected (Sjollema et al., 2016). MPs have proven to be toxic to the freshwater algae by negatively affecting the photosynthesis, which was dependent on the size, in a study dealing with the interaction of MPs and microalgae *Skeletonema costatum* (Zhang et al., 2017). Toxicity of PVC was greater than PP at certain concentrations by affecting chlorophyll-a content in *Chlorella pyrenoidosa* and *Microcystis (M.) flosaquae*. These results indicate the risk of MPs on growth of algae (Wu et al., 2019). Similar effects of PSMPs were observed in *Chlamydomonas reinhardtii*, in all different concentrations tested (Li et al., 2020d). It could recover from the toxic effect of MPs thereafter. The effects of MPs on the entire growth cycle of *Chlorella pyrenoidosa* was studied by Mao et al. (2018). It was observed that the photosynthetic activity was decreased initially but later, after logarithmic phase, an increase in the photosynthetic activity was observed. MPs/NPs do not necessarily reduce photosynthetic activity in all, some plants like *Spirodela polyrhiza* are not affected by plastic (Dovidat et al., 2020). PE MPs adhered to duckweed species, *Lemna minor* have imposed no effect on photosynthesis and growth of the weed (Mateos-Cárdenas et al., 2019). Reduced chl a and growth were noticed in case of *Chlorella vulgaris* on exposure to PSMP and metals (Cu, Zn and Mn). Combined effect showed more inhibition on growth and chl a content (Tunali et al., 2020). Long-term exposure of differently sized PSMP and PSNP on *Chlorella vulgaris* were proven to reduce cell viability, chl a and also induced stress. PS particles of varying sizes 20, 50 and

**Table 11.3** Effect of MPs/NPs on photosynthesis

Plant	MP/NP	Size	Effect	Reference
Cucumber	PSNPs	100, 300, 500, 700 nm	Reduction of chl <sub>a</sub> and chl <sub>b</sub> Oxidative stress	Li et al. (2020a, b)
Lettuce	MP PE and DBP	Not mentioned	Reduced photosynthesis	Gao et al. (2019)
Microalgae	PSMPs	0.05, 0.5, 6 µm	Photosynthesis not effected Growth affected at high concentrations of uncharged particles	Sjollema et al. (2016)
<i>Skeletonema costatum</i>	mPVC	1 µm	Photosynthesis reduced Growth inhibited	Zhang et al. (2017)
<i>Chlorella pyrenoidosa</i> <i>Microcystis (M.) flosaquae</i>	PVC, PP	Not mentioned	Reduction in chl <sub>a</sub>	Wu et al. (2019)
<i>Chlorella pyrenoidosa</i>	NP	80 nm	Growth inhibited Photosynthesis reduced Amino acyl tRNA synthetase blocked	Yang et al. (2021)
<i>Chlamydomonas reinhardtii</i>	PSMP	Not mentioned	Reduction in chl <sub>a</sub>	Li et al. (2020d)
<i>Mycrocystis aeruginosa</i>	PSNP (nPS-NH <sub>2</sub> ) + glyphosate	200 nm	Combined effect decreased chl <sub>a</sub> content but exhibited antagonistic effects PSNP decreased in chl <sub>a</sub> content at 10 and 20 mg/L Growth inhibition was observed in single agent treatment	Zhang et al. (2018)
<i>Prochlorococcus</i>	HDPE and PVC	–	Photosynthetic activity declined Growth retarded Oxygen production reduced	Tetu et al. (2019)

(continued)



**Table 11.3** (continued)

Plant	MP/NP	Size	Effect	Reference
<i>Chlorella vulgaris</i>	PSMP, Cu Zn and Mn	0.5 $\mu$ m	Reduced growth and chla content Joint effect of PSMP and metal is more toxic	Tunali et al. (2020)
<i>Chlorella vulgaris</i>	PSNP PSMP	20, 50, 500 nm	20 and 50 nm particles reduced chla concentration and cell viability Oxidative stress is induced by 20 nm	Hazeem et al. (2020)
<i>Chlorella vulgaris</i>	PS-NH <sub>2</sub>	90, 200, 300 nm	Decrease in chla and cell biomass	Khoshnamvand et al. (2021)

PSMP Polystyrene microplastic, PSNP Polystyrene nanoplastic, PE Polyethylene, PVC Polyvinyl chloride, PP Poly propylene, DBP Di-butyl phthalate, *chla* Chlorophyll a, *chl b* Chlorophyll b

500 nm were used along with PS-COOH. Smaller-sized particles declined the amount of chla and cell viability. 20 nm particles induced stress and small-sized PSNPs were responsible for cell wall damage, which was visualised by SEM and TEM (Hazeem et al., 2020). A similar study was conducted by Khoshnamvand et al. (2021) using PSNP (PS-NH<sub>2</sub>) with diameter ranging 90, 200 and 300 nm. Diameters of 90 and 200 nm decreased chla and algal biomass. These studies convey the need to focus on the adverse effects of various plastic particles on the photosynthesis of phytoplankton, which is the primary producer and major source of oxygen in aquatic ecosystems.

Yang et al. (2021) studied the interaction between nanoplastics (80 nm) and *Chlorella pyrenoidosa*. They found the inhibitory effect of nanoplastics was greater than microplastics. Nanoplastics inhibited the growth by blocking gene expression of aminoacyl t-RNA synthetase enzyme at low concentrations. At high concentrations, photosynthesis was affected. The combined effect of PSNP (nPS-NH<sub>2</sub>) and glyphosate was studied in blue-green algae, *Mycrocystis aeruginosa*. PSNP at 5 mg/L was not as toxic as glyphosate at the same concentration. But after 96 h of exposure, chla content decreased, indicating a decrease in photosynthetic activity. The integrated effect on growth indicated an antagonistic effect of PS-NH<sub>2</sub> and glyphosate (Zhang et al., 2018). The most widespread photosynthetic organism, *Prochlorococcus*, was used to study the effect of plastic leachates, HDPE and PVC. A rapid decline in the photosynthetic activity was observed at various concentrations used. Growth and oxygen production were also hindered (Tetu et al., 2019). In another research conducted by Sarker et al. (2020) on the impact of weathering on toxicity of these leachates, it was observed that toxicity declined gradually on weathering. But leachates produced even after weathering had shown to affect the growth and photosynthesis negatively. The toxicity of weathered and unweathered leachates varied on two strains of *prochlorococcus* tested. Zinc, which is the

common additive in many plastics, was found to leach after 112 days of its entry into the environment. The impact of varying concentrations of zinc on growth of *Prochlorococcus* and *Synechococcus* was also focussed on (Sarker et al., 2021).

## 11.4 Conclusion

Plants, both terrestrial and aquatic, are the primary producers and act as sinks for these plastic particles, which in turn are severely affected by them. The outcomes of the exposure of Micro and nanoplastics on photosynthetic autotrophs are focussed on in the present chapter. Most of the research claimed the toxic effects of MPs/NPs on plants. Their toxicity is dependent on the type, size and concentration being employed. MPs/NPs exhibit direct effects by altering plant growth or indirectly by altering soil properties or soil microbial interaction, which will impair plant performance. The positive impact of these particles on plant growth is also witnessed in certain cases. Phytoplankton, which is an important primary producer and source of oxygen, is also negatively affected by the MPs/NPs that get accumulated in aquatic ecosystems in various ways. The effects of weathering on toxicity of plastic leachates on phytoplankton are also being investigated. MPs/NPs act as carriers of many toxic compounds that exhibit harmful effects on plants. The researches focussed on the effects of micro and nanoplastics on agricultural crops recommend focusing on safety of food and human health, as the internalised particles might get transferred at trophic levels. So, there is a need to encourage and focus our research on the impact of plastic pollution on plant functionalities.

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