RESEARCH ARTICLE

Investigating the Impact of Microplastics Type of Polyethylene, Polypropylene, and Polystyrene on Seed Germination and Early Growth of Rice Plants

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ABSTRACT

Microplastics (MPs), which are emerging pollutants in terrestrial ecosystems, could potentially impact plant growth. One of the least explored aspects of crop development is seed germination, a crucial stage in the plant's lifecycle. This study conducted soil cultivation trials to investigate the effects of 1% (w/w) concentrations of polyethylene (PET), polypropylene (PP), and polystyrene (PS) MPs on rice growth over a 15-day period. Parameters such as fresh weight, shoot height, root length, chlorophyll levels, and MPs identification in the roots were observed. The findings revealed the accumulation of 6–9 MP items in the roots. PET MPs inhibited root elongation (15%–20%), reduced shoot height (15%–30%), and decreased rice fresh weight (12%–37%). MPs PET, PP, and PS contamination reduced the content of chlorophyll *a* (15%–43%), *b* (21%–41%), and total (11%–40%) in rice leaves. This study enhances our understanding of the ecotoxicological effects of these three types of MPs on rice. The utilization of this data will further inform our understanding of MPs' behavior in soil vegetation and provide valuable insights into their land-based impacts.

1 | Introduction

In recent decades, the proliferation of plastic materials has led to widespread environmental contamination (Bao et al. 2022), with microplastics (MPs), emerging as a major concern due to their minute size and potential long-term effects on ecosystems (Boots, Russell, and Green 2019). MPs, defined as plastic particles with dimensions less than 5 mm (Sathish et al. 2022), have infiltrated various environmental compartments, including soil (Accinelli et al. 2022), organic fertilizer (Iswahyudi et al. 2024), water (Blettler et al. 2019; Grbić et al. 2020; Sembiring et al. 2020), and air (Aini, Syafiuddin, and Bent 2022; Aini, Syafiuddin, and Kueh 2023). Recently, MPs were found at 67.5 ± 65.6 items/m^3 in the Lijiang River in Guangxi, China (Zhang et al. 2021). In Atoyac, Mexico, the total number of MPs was 1633.34 ± 202.56 items/kg in sediment (Shruti et al. 2019) and high MPs concentrations ranging between 8.7×10^3 and 1.4×10^4/kg were found in soil (Crossman et al. 2020). The consequences of this pervasive contamination extend to agricultural landscapes, posing a potential threat to crop plants and humans.

MPs in agricultural soils can originate from various sources (de Souza et al. 2019; Fan et al. 2023), including the breakdown of larger plastic debris (Ayilara et al. 2020), the application of plastic mulches (Campanale et al. 2022), compost (Braun et al. 2021; Edo, Fernández-Piñas, and Rosal 2022), and the use of plastic-based agrochemical formulations (Gui et al. 2021). These particles have been detected in soils worldwide (Briassoulis 2023), and their persistence raises questions about potential adverse effects on plant physiology, development, and overall crop productivity (Chang et al. 2022). Additionally, the presence of MPs may have detrimental effects on the soil's microbial population (Liu et al. 2019). The concurrent presence of numerous contaminants leads to significant deterioration of soil health. Moreover, it has been observed that the presence of MPs in soil can impede the seed germination process and can also be transferred from the roots to the stems and leaves, resulting in disturbances in plant growth (de Souza et al. 2019).

> "*MPs can enter the human body through inhalation, ingestion, or consumption of contaminated food and beverages.*"

MPs have several negative effects on plants, including (i) obstructing the ingestion and movement of plant nutrients by blocking openings in the cytoplasmic wall or interactions between cells and inhibiting photosynthesis (Yang et al. 2021), (ii) lowering or delaying seed germination by impeding water uptake, (iii) altering root and shoot growth and development (Boots, Russell, and Green 2019; Bosker et al. 2019), and (iv) causing other ecotoxicological and genotoxic effects (Qi et al. 2018). It has been found that MPs might be ingested by humans when consuming agricultural goods (Zhou et al. 2023). MPs can enter the human body through inhalation, ingestion, or consumption of contaminated food and beverages. They can cause various immune system problems, such as weakening or activating the immune system and triggering abnormal inflammatory reactions. Additionally, MPs can induce stress, reproductive issues, and growth abnormalities (Wu et al. 2022).

> "*More than half of the world's population relies on rice as their primary food source.*"

More than half of the world's population relies on rice as their primary food source (Huang et al. 2020). Thailand, Malaysia, Philippines, and Pakistan are the top four Asian rice-producing countries (Wang et al. 2020b). Furthermore, investigating the effects of MPs on rice plants is crucial. In fact, there have been few studies examining how MPs affect rice seedlings. Most of the research in this area has focused on non-food crops. For example, when cress (*Lepidium sativum*) was exposed to MPs, it hindered root growth (Bosker et al. 2019). Exposure to polyethylene (PET) MPs reduced germination rates by 16.66% in tomato (*Solanum lycopersicum* L.) and blackgram (*Vigna mungo* L.). It was suggested by de Silva et al. (2022) that PE MPs on lentils (*Lens culinaris*) might physically block pores, thereby inhibiting later growth. To date, only one study has examined the impact of MPs on rice (*Oryza sativa L.*) seedlings, which were hydroponically cultured. Seedlings exposed to polystyrene (PS) nanoplastics (NPs) exhibited a reduction in root length and an increase in the number of lateral roots (Zhou et al. 2021). However, this study was limited to a single plastic polymer and conducted under hydroponic conditions. To the best of the authors' knowledge, no studies have exclusively described the impact of various MPs polymers on rice seedlings. Therefore, rice emerges as a suitable model for investigating the plant's response to various MPs under standard agricultural practices. The MPs used in this study were PS, polypropylene (PP), and PET. The choice of the type of MPs used in the study on the impact of MPs on rice seedlings was based on several important reasons. These three types of MPs are the most common types found in agricultural environments, including soil (Ding et al. 2020; Du et al. 2020), compost (Iswahyudi et al. 2024), and irrigation water (Garfansa et al. 2024). Then, PET, PP, and PS are types of MPs that have different chemical and physical characteristics (Hamidian et al. 2021), allowing the study to explore their different impacts on rice plants. Furthermore, the use of equal concentrations of these three types of MPs allows evaluation of the possible toxic effects of different types of MPs exposure. Consequently, this study aims to build upon this knowledge, focusing specifically on the unique characteristics of rice plants and their susceptibility to MPs induced stress during the critical early growth stages. The novelty of this study lies in gaining a better understanding of the mechanisms underlying the effects of MPs on rice and documenting the toxic effects of MPs on rice, including assessments of fresh weight, shoot height, root length, MPs presence in the roots, and chlorophyll (*Chl*) analysis.

2 | Materials and Methods

2.1 | Materials

Plastics used in this study were purchased from plastic distributors Sinar Plastik (Pamekasan city, East Java province, Indonesia) and plastics brand Gading. Chemicals methanol, acetone, hydrogen peroxide (H_2O_2), and ferrous sulfate liquid (Fe_2SO_4) were purchased from Kimia Farma company (Pamekasan city, East Java province, Indonesia). The rice seeds were (*Oryza sativa* L.) Inpari-32 variety.

2.2 | Experimental Setup and Treatment

In this study, MP particles of PET, PP, and PS with a diameter of 200–250 μm and a purity of ≥97% were obtained by crushing plastic materials with a blender. The MP particles were subjected to methanol wash to eliminate surface chemicals soluble in the solvent. Following the approach outlined by Bandow et al. (2017), the MPs underwent artificial aging at 80°C for 360 h to simulate their outdoor degradation and were subsequently stored at 4°C prior to utilization. The rice seeds used were of the Inpari-32 variety. Yellow—brown soil with a pH of 6.21 and organic matter content of 1.14% was collected from Banyupelle Village, Pamekasan, located in the East Java province of Indonesia. Before it was used, the soil was brought to room temperature and dried by air. It was then put through a 1-mm mesh screen. Three types of plastics mixed with sterilized soil as much as 1% w/w for each treatment. The soil after being treated with plastic was then left for 4 weeks and was ready for planting rice seeds. For the experimental setup (**Exhibit 1**), the method proposed by Liu et al. (2021) was used as the basis.

> "*The study in trays aims to evaluate the impact of each type of MPs polymer on rice seed growth.*"

The study in trays aims to evaluate the impact of each type of MPs polymer on rice seed growth. The treatment consisted of control

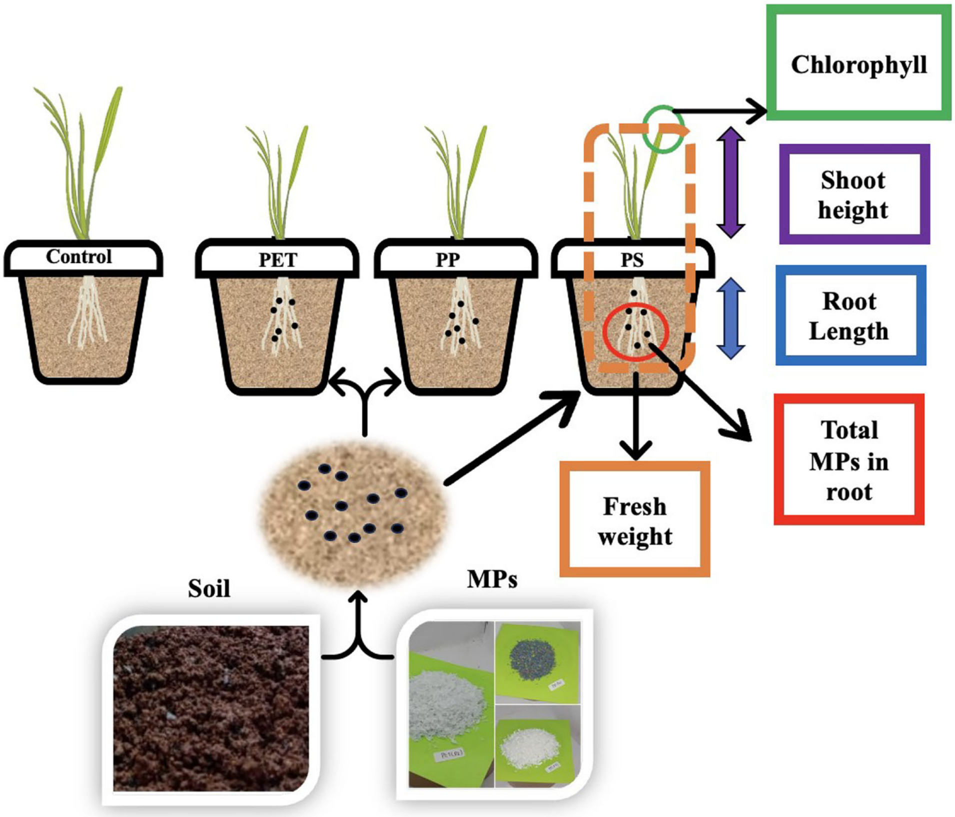

EXHIBIT 1 | Schematic experimental setup. [Color figures can be viewed at wileyonlinelibrary.com.]

(soil without mixed with MPs), soil with PET, soil with PP, and soil with PS. MPs were given at a concentration of 1% (w/w) for each experiment. The tray had a dimension of 40 × 30 × 4 cm containing 2000 g of soil. Watering was given as much as 60% for 48 h. The seeds were soaked in H_2O_2 for 30 min. Total of 40 rice seeds were spread into trays for 15 days. The growth analysis conducted encompassed the examination of shoot height, root length, and the fresh weight of both the shoot and the root.

2.3 | Determination Chlorophyll and Identification MPs

The contents of Chl *a*, Chl *b*, and total Chl were assessed after 15 days of growth. For this analysis, 0.1 g of fresh leaves from each treatment group were weighed and finely ground using a porcelain mortar before being mixed with 10 mL of acetone solution. The mixture was then placed in a tube and centrifuged to separate the extract from the leaf debris. Absorbance was measured with a spectrophotometer (Shimadzu UV-1800 UV-VIS Spectrophotometer, Tokyo, Japan) after transferring the extract into a cuvette, at wavelengths of 662 and 644 nm. The UV-VIS spectra of the acidified supernatants were recorded within the specified range, immediately after adding the acidic solution and subsequently at two-minute intervals for 20 minutes. A final scan was done 24 hours later to check for temporal variations. Before the final scan, samples were stored in refrigerated, dark-brown opaque containers. The standard UV-VIS concentration for extracts in acetone was Chl *a* max 86.3 $g^{-1}\ cm^{-1}$ and Chl *b* max 20.49 $g^{-1}\ cm^{-1}$ (Lichtenthaler and Buschmann 2001). Calibration of the UV-VIS spectrophotometer for chlorophyll concentration measurements generally involved preparing standard solutions of known chlorophyll concentrations and measuring their absorbance with the spectrophotometer (Sobiechowska-Sasim, Stoń-Egiert, and Kosakowska 2014). The procedure followed was detailed by Zhu et al. (2019).

2.4 | Identification of MPs in Roots

The identification of MPs was performed on plant roots. For each treatment, the roots were submerged in a solution containing 30% H_2O_2 (20 mL) and 10 drops of Fe_2SO_4. After 24 hours of incubation to allow disintegration, the mixture was centrifuged and then placed in a water bath at 70°C for 30 minutes. The sample was then prepared for examination using a stereo microscope, which involved counting MPs and measuring particle sizes in the roots. This analysis followed the method proposed by Junhao et al. (2021).

2.5 | Statistical Analysis

The average and standard deviation for fresh weight, shoot height, root length, and chlorophyll in each treatment were computed and reported. IBM SPSS Statistics 24 was employed for statistical analysis, and the results were conveyed as mean standard deviation (SD). Statistical differences among treatments were assessed using one-way analysis of variance (ANOVA) and Duncan's test ($p < 0.05$).

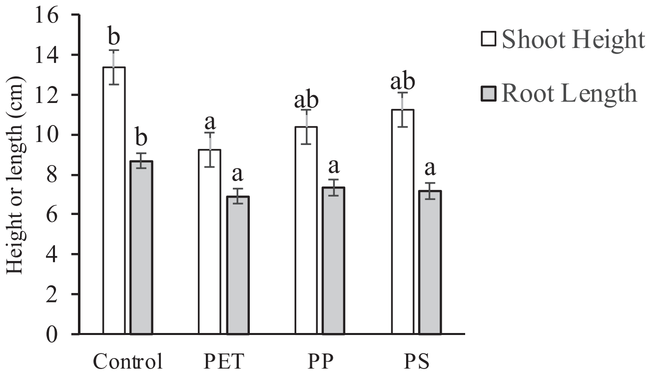

EXHIBIT 2 | Shoot rice's height and root length for different MPs. Error bars represent standard deviation for each treatment. Different letters for each parameter indicate a significant difference at $p < 0.05$.

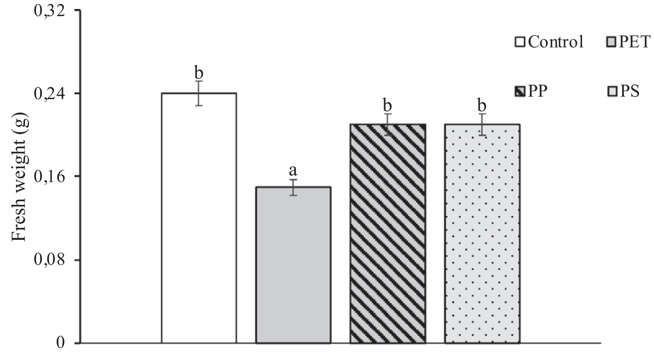

EXHIBIT 3 | Fresh plant weight of rice for different MPs. Error bars represent standard deviation for each treatment. Different letters for each parameter indicate a significant difference at $p < 0.05$.

3 | Results and Discussion

3.1 | Effect of MPs on Rice Growth

Exhibit 2 illustrates the impact of three types of MPs (PET, PP, and PS) on both shoot height and root length. The presence of PET in the soil can reduce the shoot height from 13 (control) to 9 cm. In comparison, PP and PS reduced shoot height from 13 (control) to 10 cm and from 13 (control) to 11 cm, respectively. Generally, PET caused the greatest reduction in the shoot height. This reduction may be attributed to blockages on the surface of seed pores, preventing water absorption. Plastic particulates likely contributed to these obstructions, thereby delaying shoot height.

The rice shoot height exhibited a notable decrease in all three MPs treatments. However, a significant distinction in the reduction of shoot height was observed only in the PET MPs treatment compared to the control ($p > 0.05$). Support this study, MPs can affect the decrease in shoot height observed by Bosker et al. (2019) in a terrestrial plant (cress; *Lepidium sativum*), blackgram (*Vigna mungo* L.), and tomato (*Solanum lycopersicum* L.) (Sahasa et al. 2023). The shoot height was significantly reduced by 5%–8% in wheat (Liu et al. 2021).

In contrast, the root length of rice was relatively similar for all MP treatments (Exhibit 2). The presence of PET in the soil reduced root length from 9 (control) to 7 cm. In comparison, PP and PS reduced root length from 9 (control) to 7.5 cm and from 9 (control) to 7.2 cm, respectively. Generally, PET caused the greatest reduction in root length. This reduction in root length could be attributed to plastic particles making it harder for the plant to absorb water and nutrients. Root formation or growth was slowed down, and roots were less likely to survive.

The length of the rice roots differed between the control category and the MPs treatment ($p < 0.05$). Previous studies on the effects of MPs stress on wheat seedlings and roots revealed a significant reduction in their length and height (Lian, Wu, and Xiong 2020). Silva et al. (2021) also reported that stress due to MPs contamination in plants can decrease root growth. MP residues on farms have various potential detrimental consequences on plant growth (Chang et al. 2022). In our work, MPs greatly decrease shoot height, whereas rice shoot height was significantly reduced when contaminated with PET MPs compared to PP and PS. Additionally, Liu et al. (2021) reported that root elongation occurs with an increase in MPs concentration in plants. Corroborating this, Zhang et al. (2020) discovered that MPs caused an 8% decline in the groundwater infiltration rate. This situation might subject plant roots to moderate water stress, ultimately resulting in root elongation.

As growth time progressed, the fresh plant/shoot weight increased normally in the control treatment and decreased in the presence of MPs contamination. As shown in **Exhibit 3**, there was a clear trend of decreasing the shoot weight for all the MPs treatment compared to control. The presence of PET in the soil reduced the fresh plant from 0.24 (control) to 0.15 g. In comparison, PP and PS reduced the fresh plant from 0.24 (control) to 0.21 g. Generally, PET caused the greatest reduction in fresh plant weight. This suggests that reducing shoot height and root length has a significant impact on shoot weight. There was a significant decrease in rice fresh weight ($p < 0.05$) observed in the PET MPs treatment compared to the other treatments. Huang et al. (2023) noted a reduction in plant root biomass due to MPs, which aligns with our findings. The decrease in soil porosity and aeration, attributed to the reduction in soil density caused by PET MPs (Li et al. 2023a; Yu et al. 2022), may hinder plant root growth in the soil. Roots with less weight have a harder time taking in water and nutrients, as well as experiencing reduced microbial activity and mycorrhizal integration. This consequently leads to a decline in aboveground plant growth (Barnawal et al. 2013).

3.2 | Effects on MPs Accumulation in Rice Seedling Roots

In all treatments where plants were exposed to MPs, clear evidence of MPs was observed in the roots. This observation was in stark contrast to the control treatment, where no MPs were detected (as illustrated in **Exhibit 4**). The data revealed varying degrees of MPs presence across different treatments. Specifically, the treatments with the highest concentrations of MPs were PET, PP, and PS, with respective counts of 9, 7, and 6 MPs items observed per sample area. In contrast, the control treatment showed no presence of MPs, indicating that the contamination observed in the other treatments was indeed due to the introduction of MPs.

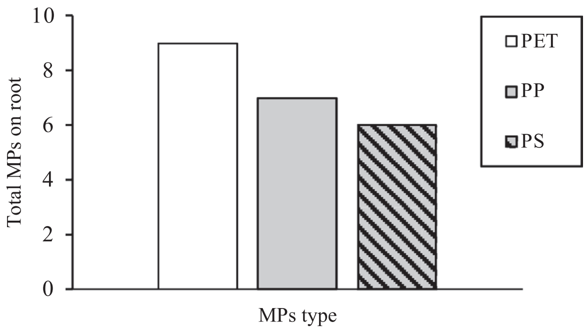

EXHIBIT 4 | Total MPs in root in rice for different MPs.

This finding highlights the ability of MPs, particularly those composed of PET, PP, and PS, to accumulate within the root systems of plants. The differing counts of MPs among the treatments suggest variations in the uptake and retention of MPs by the plants, possibly influenced by factors such as MPs size, composition, and environmental conditions. Furthermore, this indicates that PET MPs were mostly absorbed by roots, likely carried away during the uptake of water. This may be due to the different chemical and physical properties of PET MPs. PET MPs tend to absorb dangerous chemicals more easily from the surrounding environment and carry them into plant tissue, including roots. Additionally, PET's more complex molecular structure may also make it difficult for soil microorganisms to decompose, allowing for greater accumulation over a longer period. The accumulation of PET MPs in plants roots can disrupt plant physiological processes, such as nutrient and water absorption, and affect the balance of soil microbiota which is important for plant health. In general, an increase in the quantity of MPs would result in a decrease in both root growth and shoot height, as depicted in Exhibit 2. This suggests that MPs have the potential to diminish nutrient absorption by plants in the soil.

MPs can interfere with plant photosynthesis through several mechanisms that were still not fully understood. One possible mechanism was when MPs dissolved in irrigation water and absorbed by plant roots can disrupt the photosynthesis process by interfering with the transport of water and nutrients in plants, which was necessary for optimal photosynthesis. In addition, MPs that accumulate in the soil can also disrupt the balance of soil microbes that play a role in the nutrient cycle and the availability of nutrients for plants, which in turn can affect the health and efficiency of plant photosynthesis.

MPs can hinder plant roots' ability to absorb nutrients. These particles can become lodged in tiny crevices around the roots, impeding the uptake of essential water and nutrients necessary for plant growth (Dong et al. 2021). Additionally, MPs can compromise the permeability of plant roots by forming a film that obstructs the flow of water and air in and out of the roots, disrupting vital gas and moisture exchange crucial for plant development (Ullah et al. 2021). Several types of MPs contain harmful chemicals, such as plastic additives and organic pollutants, which can adhere to them. Exposure of plant roots to MPs containing toxic substances can lead to poisoning, hindering the plants' growth and development (Costa et al. 2023). Moreover, MPs can interact with soil microorganisms, crucial players in maintaining soil ecosystem balance. These interactions can affect the health of soil microorganisms, subsequently influencing nutrient availability and nutrient cycles essential for plant nutrition (Yuan et al. 2023).

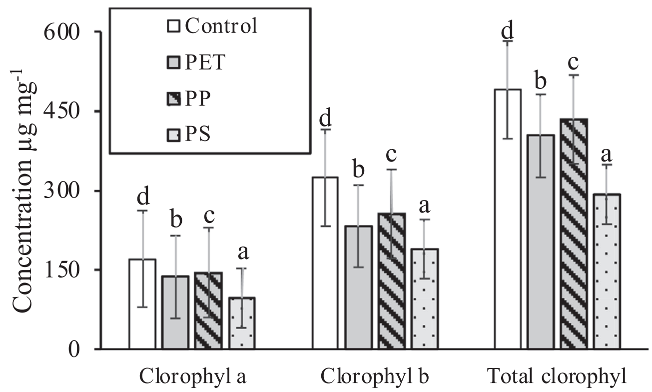

EXHIBIT 5 | Chlorophyll *a*, *b*, and total concentration in rice for different MPs. Different letters for each parameter indicate a significant difference at $p < 0.05$.

3.3 | Effects on Photosynthesis

To calculate the impact of different types of MPs on rice photosynthesis, the concentrations of detected Chl *a*, Chl *b*, and total Chl in rice leaves were measured after a 15-day treatment period, as illustrated in **Exhibit 5**. In the presence of MPs contamination, the concentrations of Chl *a*, Chl *b*, and total Chl all decreased, resulting in a reduction in total Chl. Under PET exposure conditions, there was a significant decrease in chlorophyll concentration, with an average decrease of 20% for Chl *a*, 28% for Chl *b*, and 18% for total Chl. Meanwhile, under conditions of PP exposure, there was a lower decrease in Chl concentration compared to PET exposure, with an average decrease of 15% for Chl *a*, 21% for Chl *b*, and 11% for total Chl. Under PS exposure conditions, the most significant decrease in Chl concentration occurred, with an average decrease of 43% for Chl *a*, 41% for Chl *b*, and 40% for total Chl. Thus, the data pattern shows that PS exposure has the greatest impact on reducing Chl concentration in rice seedlings, followed by PET and then PP.

These percentages of Chl *a*, Chl *b*, and total Chl were significantly lower than those of the control ($p < 0.05$), indicating that MPs severely compromised the photosynthetic system of rice. Several studies have shown a decrease in Chl content in plants exposed to MPs. Exposure to MPs can interfere with plant photosynthesis, which is an important process in Chl production. This interference can reduce Chl production and consequently inhibit plant growth and development. These findings align with those of Wang et al. (2020a), whose study demonstrated a decrease in total Chl concentration due to MPs. Stimulating the photosynthetic system under low MPs concentrations could result in a reduction in rice biomass, as depicted in Exhibit 3. In comparison to pollution solely from PE-MPs, the addition of phenanthrene led to a significant decrease in both Chl *a* and carotenoids ($p < 0.05$).

EXHIBIT 6 | Summarized findings of present and previous studies.

Research object	MPs type	Exposure condition	Impacts	Reference
Rice seedlings	PET, PP, PS	1%	Reduced shoot height, rice fresh weight, and chlorophyll content	Present study
Rice seedlings	PS & PTFE	0.2 gL^{-1} and 4 mgL^{-1}	Decreased biomass and inhibited photosynthesis	(Dong et al. 2020)
Maize seedlings	PE	10%	Inhibited photosynthesis and the accumulation of arsenic	(Sun et al. 2023)
Wheat seedlings	PE	0.2%	Reduced biomass and height and promoted carotenoid content and peroxidase activity	(Guo et al. 2022)
Lentil seedlings	PE	10–100 mgL^{-1}	Reduced the internal activity during germination of the seeds	(de Silva et al. 2022)
Blackgram and Tomato	PE	0.25%–1%	Reduced germination and root length	(Sahasa et al. 2023)

The majority of Chl *a* and Chl *b* were capable of absorbing and transmitting light energy. Under special conditions, only a few Chl *a* molecules can convert light energy (Li, Zeng, and Sun 2023b). The Chl *a* to Chl *b* ratio decreased because of the relative changes. This behavior was seen in spinach that was grown in dirt that had MPs in it. MPs may improve photon conductivity and then cause too many electrons to form triplet chlorophyll and singlet oxygen, damaging chlorophyll and photosynthetic capacity in a way that cannot be fixed (Takagi et al. 2016). In a previous report, the concentrations of Chl *a* and Chl *b* in wheat and melon treated with MPs, showed a negative impact on plant growth (Li, Zeng, and Sun 2023b; Liu et al. 2021). Therefore, the type of MPs will affect the rice photosynthetic system. However, it was important to note that study into the effects of MPs on plant Chl content was still in its infancy, and further study was needed to better understand the mechanisms and impacts involved.

3.4 | Effects of MPs on Seedling

MPs were found to have had negative effects on seedling growth see on **Exhibits 6** and **7**. Studies showed that the presence of PE-MPs led to a decline in germination rate and a reduction in root and shoot characteristics of plants (Sahasa, Dhevagi, and Poornima 2023). Lentil seeds that were exposed to PE-MPs also exhibited reduced internal activity during germination, possibly due to physical blockage of pores (De Silva et al. 2022). Furthermore, Dong et al. (2020) observed PS and PTFE MPs on rice seedlings cause decreased biomass and inhibited photosynthesis. While in maize seedlings, PE-MPs also inhibited photosynthesis and the accumulation of arsenic (Sun, Shi, and Zhao 2023). PE-MPs also reduced the biomass and height, too promoted carotenoid content and peroxidase activity in wheat seedling (Guo et al. 2022). MPs had different effects on plant growth based on the type of plant and the type of plastic used. These effects could lead to changes in the composition of plant communities and primary production (Rillig et al. 2019). Overall, MPs were found to hinder seedling growth and could have significant impacts on plant performance.

Comparing the impact of MPs with other contaminants that impact plants will provide a more comprehensive understanding of the risks associated with each pollutant. Some other contaminants that can be compared to MPs in this context include heavy metals such as lead, cadmium, and mercury, as well as pesticides and herbicides used in agriculture. Although MPs have recently received increasing attention in environmental research, their impact on plants was still not fully understood. However, the ability of MPs to disrupt plant growth processes and accumulate in plant tissues represents a significant potential hazard (Azeem, Adeel, and Ahmad 2021). Furthermore, the accumulation of heavy metals in plants can disrupt various physiological processes, including photosynthesis, respiration, and metabolism, which can cause plant damage and death (Nagajyoti, Lee, and Sreekanth 2010; Riyazuddin et al. 2022). Meanwhile, pesticides and herbicides can also disrupt plant metabolism, cause tissue damage, and even disrupt the plant's reproductive system. Some pesticides and herbicides can have negative impacts on plants if used excessively or inappropriately, including poisoning plant tissue, disrupting the hormonal system, and inhibiting growth (Alengebawy et al. 2021; Kamal, Ahmad, and Shafeeque 2020). In many cases, the impact of pollutants on plants can be influenced by interactions between the pollutants, as well as by environmental and genetic factors. Therefore, to determine which pollutants are most dangerous for plants, it was necessary to carry out further study and comprehensive evaluations to understand their impacts better.

3.5 | The Possible Impact of MPs on Public Health

The discovery of MPs in plants such as rice has serious implications for public health. MPs that accumulate in food crops can enter the human food chain, increasing the risk of MPs exposure for consumers (Mamun et al. 2023). In addition, dangerous chemicals attached to MPs can disrupt the human hormonal system and cause various diseases (Campanale et al. 2020). The long-term impact of exposure to MPs on human health was still not fully understood, but early study suggests links to health problems such as reproductive disorders, immune system

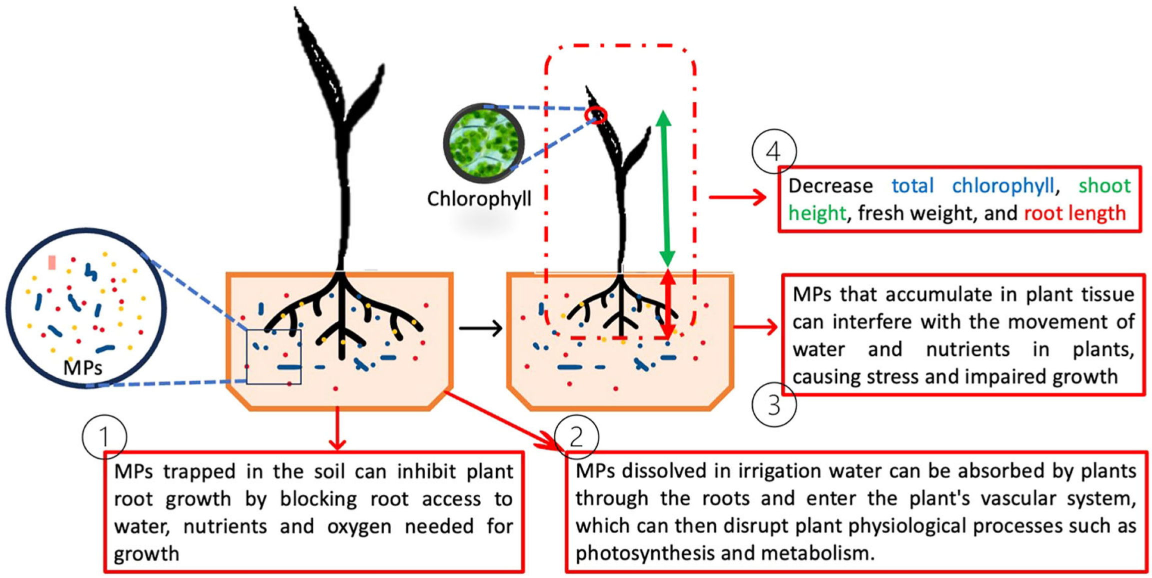

EXHIBIT 7 | The mechanism how MPs can affect the plant. [Color figures can be viewed at wileyonlinelibrary.com.]

disorders, and even cancer (Prata et al. 2020). In addition, very small MPs particles can be easily inhaled by humans, enter the lungs, and cause irritation or infection, potentially leading to chronic respiratory problems (Blackburn and Green 2022). In addition, MPs contaminated by pathogenic microorganisms can also be a source of disease transmission for humans through consuming contaminated food (Junaid et al. 2022). Apart from the direct impact on human health, MPs pollution can also have a psychological impact, increasing anxiety and concerns about the quality of food and the environment which causes mental stress in society (Masud, Islam, and Mamun 2024; Thoma, Rohleder, and Rohner 2021). Therefore, the discovery of MPs in food crops should be a serious warning for the government and society to take preventive action to reduce plastic use and create a more effective waste management system (Igalavithana et al. 2022).

4 | Conclusion

The findings of this study showed indications that the presence of MPs in soil results in significant levels of toxicity. There were 6–9 items MPs accumulated in the roots, PET inhibited root elongation while PP and PS stimulated rice root elongation but did not increase aboveground rice biomass. The highest amount of MPs absorption in roots was treated with PET. Thus, in the PET treatment, there was a tendency to inhibit rice growth. For the photosynthetic pigment of rice leaves, PET inhibits its synthesis. The findings provide new insights into the toxicity of MPs to plants. To protect the environment and plants, it is important to reduce the excessive use and disposal of PET plastic and other types of MPs in general, as well as promote responsible plastic waste management practices. Future studies need to be carried out to conduct experiments on other plant seeds.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

References

Accinelli, C., H. K. Abbas, V. Bruno, et al. 2022. "Field Studies on the Deterioration of Microplastic Films From Ultra-Thin Compostable Bags in Soil." *Journal of Environmental Management* 305: 114407–114415. https://doi.org/10.1016/j.jenvman.2021.114407.

Aini, S. A., A. Syafiuddin, and G.-A. Bent. 2022. "The Presence of Microplastics in Air Environment and Their Potential Impacts on Health." *Environmental and Toxicology Management* 2, no. 1: 31–39. https://doi.org/10.33086/etm.v2i1.2900.

Aini, S. A., A. Syafiuddin, and A. B. H. Kueh. 2023. "Quantification, Characteristics, and Distribution of Microplastics Released from Waste Burning Furnaces and Their Associated Health Impacts." *Environmental Quality Management* 33, no. 1: 303–310. https://doi.org/10.1002/tqem.22056.

Alengebawy, A., S. T. Abdelkhalek, S. R. Qureshi, and M.-Q. Wang. 2021. "Heavy Metals and Pesticides Toxicity in Agricultural Soil and Plants:

Ecological Risks and Human Health Implications." *Toxics* 9, no. 3: 42–75. https://doi.org/10.3390/toxics9030042.

Ayilara, M. S., O. S. Olanrewaju, O. O. Babalola, and O. Odeyemi. 2020. "Waste Management Through Composting: Challenges and Potentials." *Sustainability* 12, no. 11: 4456–4479. https://doi.org/10.3390/su12114456.

Azeem, I., M. Adeel, M. A. Ahmad, et al. 2021. "Uptake and Accumulation of Nano/Microplastics in Plants: A Critical Review." *Nanomaterials* 11, no. 11: 2935–2957. https://doi.org/10.3390/nano11112935.

Bandow, N., V. Will, V. Wachtendorf, and F.-G. Simon. 2017. "Contaminant Release From Aged Microplastic." *Environmental Chemistry* 14, no. 6: 394–405. https://doi.org/10.1071/EN17064.

Bao, R., Z. Wang, H. Qi, et al. 2022. "Occurrence and Distribution of Microplastics in Wastewater Treatment Plant in a Tropical Region of China." *Journal of Cleaner Production* 349: 131454–131464. https://doi.org/10.1016/j.jclepro.2022.131454.

Barnawal, D., D. Maji, N. Bharti, C. S. Chanotiya, and A. Kalra. 2013. "ACC Deaminase-Containing Bacillus Subtilis Reduces Stress Ethylene-induced Damage and Improves Mycorrhizal Colonization and Rhizobial Nodulation in Trigonella Foenum-graecum Under Drought Stress." *Journal of Plant Growth Regulation* 32, no. 4: 809–822. https://doi.org/10.1007/s00344-013-9347-3.

Blackburn, K., and D. Green. 2022. "The Potential Effects of Microplastics on Human Health: What Is Known and What Is Unknown." *Ambio* 51, no. 3: 518–530. https://doi.org/10.1007/s13280-021-01589-9.

Blettler, M. C. M., N. Garello, L. Ginon, E. Abrial, L. A. Espinola, and K. M. Wantzen. 2019. "Massive Plastic Pollution in a Mega-River of a Developing Country: Sediment Deposition and Ingestion by Fish (Prochilodus lineatus)." *Environmental Pollution* 255: 113348–113368. https://doi.org/10.1016/j.envpol.2019.113348.

Boots, B., C. W. Russell, and D. S. Green. 2019. "Effects of Microplastics in Soil Ecosystems: Above and Below Ground." *Environmental Science & Technology* 53, no. 19: 11496–11506. https://doi.org/10.1021/acs.est.9b03304.

Bosker, T., L. J. Bouwman, N. R. Brun, P. Behrens, and M. G. Vijver. 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. https://doi.org/10.1016/j.chemosphere.2019.03.163.

Braun, M., M. Mail, R. Heyse, and W. Amelung. 2021. "Plastic in Compost: Prevalence and Potential Input Into Agricultural and Horticultural Soils." *Science of the Total Environment* 760: 143335–143350. https://doi.org/10.1016/j.scitotenv.2020.143335.

Briassoulis, D. 2023. "Agricultural Plastics as a Potential Threat to Food Security, Health, and Environment Through Soil Pollution by Microplastics: Problem Definition." *Science of the Total Environment* 892: 164533–164543. https://doi.org/10.1016/j.scitotenv.2023.164533.

Campanale, C., S. Galafassi, I. Savino, et al. 2022. "Microplastics Pollution in the Terrestrial Environments: Poorly Known Diffuse Sources and Implications for Plants." *Science of the Total Environment* 805: 150431–150440. https://doi.org/10.1016/j.scitotenv.2021.150431.

Campanale, C., C. Massarelli, I. Savino, V. Locaputo, and V. F. Uricchio. 2020. "A Detailed Review Study on Potential Effects of Microplastics and Additives of Concern on human Health." *International Journal of Environmental Research and Public Health* 17, no. 4: 1212–1222. https://doi.org/10.3390/ijerph17041212.

Chang, X., Y. Fang, Y. Wang, F. Wang, L. Shang, and R. Zhong. 2022. "Microplastic Pollution in Soils, Plants, and Animals: A Review of Distributions, Effects and Potential Mechanisms." *Science of the Total Environment* 850: 157857. https://doi.org/10.1016/j.scitotenv.2022.157857.

Costa, J. P. d., A. Avellan, C. Mouneyrac, A. Duarte, and T. Rocha-Santos. 2023. "Plastic Additives and Microplastics as Emerging Contaminants: Mechanisms and Analytical Assessment." *TrAC Trends in Analytical Chemistry* 158: 116898. https://doi.org/10.1016/j.trac.2022.116898.

Crossman, J., R. R. Hurley, M. Futter, and L. Nizzetto. 2020. "Transfer and Transport of Microplastics From Biosolids to Agricultural Soils and the Wider Environment." *Science of the Total Environment* 724: 138334. https://doi.org/10.1016/j.scitotenv.2020.138334.

De Silva, Y. S. K., U. M. Rajagopalan, H. Kadono, and D. Li. 2022. "Effects of Microplastics on Lentil (Lens culinaris) Seed Germination and Seedling Growth." *Chemosphere* 303: 135162–135170. https://doi.org/10.1016/j.chemosphere.2022.135162.

de Souza, A. A. M., C. W. Lau, W. Kloas, et al. 2019. "Microplastics Can Change Soil Properties and Affect Plant Performance." *Environmental Science & Technology* 53, no. 10: 6044–6052. https://doi.org/10.1021/acs.est.9b01339.

Ding, L., S. Zhang, X. Wang, et al. 2020. "The Occurrence and Distribution Characteristics of Microplastics in the Agricultural Soils of Shaanxi Province, in North-Western China." *Science of the Total Environment* 720: 137525–137535. https://doi.org/10.1016/j.scitotenv.2020.137525.

Dong, Y., M. Gao, W. Qiu, and Z. Song. 2021. "Uptake of Microplastics by Carrots in Presence of As (III): Combined Toxic Effects." *Journal of Hazardous Materials* 411: 125055–125070. https://doi.org/10.1016/j.jhazmat.2021.125055.

Dong, Y., M. Gao, Z. Song, and W. Qiu. 2020. "Microplastic Particles Increase Arsenic Toxicity to Rice Seedlings." *Environmental Pollution* 259: 113892–113899. https://doi.org/10.1016/j.envpol.2019.113892.

Du, C., H. Liang, Z. Li, and J. Gong. 2020. "Pollution Characteristics of Microplastics in Soils in Southeastern Suburbs of Baoding City, China." *International Journal of Environmental Research and Public Health* 17, no. 3: 845–855. https://doi.org/10.3390/ijerph17030845.

Edo, C., F. Fernández-Piñas, and R. Rosal. 2022. "Microplastics Identification and Quantification in the Composted Organic Fraction of Municipal Solid Waste." *Science of the Total Environment* 813: 151902–151920. https://doi.org/10.1016/j.scitotenv.2021.151902.

Fan, W., C. Qiu, Q. Qu, et al. 2023. "Sources and Identification of Microplastics in Soils." *Soil & Environmental Health* 1, no. 2: 100019–100030. https://doi.org/10.1016/j.seh.2023.100019.

Garfansa, M. P., L. Zalizar, S. Husen, J. Triwanto, I. Iswahyudi, and Y. A. C. Ekalaturrahmah. 2024. "Fate and Distribution of Microplastics in Water and Sediment Collected From Samiran Ditch Irrigation." *Environmental Quality Management* 35, no. 1: 22204–22218. https://doi.org/10.1002/tqem.22204.

Grbić, J., P. Helm, S. Athey, and C. M. Rochman. 2020. "Microplastics Entering Northwestern Lake Ontario Are Diverse and Linked to Urban Sources." *Water Research* 174: 115623–115633. https://doi.org/10.1016/j.watres.2020.115623.

Gui, J., Y. Sun, J. Wang, X. Chen, S. Zhang, and D. Wu. 2021. "Microplastics in Composting of Rural Domestic Waste: Abundance, Characteristics, and Release From the Surface of Macroplastics." *Environmental Pollution* 274: 116553–116566. https://doi.org/10.1016/j.envpol.2021.116553.

Guo, A., C. Pan, X. Su, X. Zhou, and Y. Bao. 2022. "Combined Effects of Oxytetracycline and Microplastic on Wheat Seedling Growth and Associated Rhizosphere Bacterial Communities and Soil Metabolite Profiles." *Environmental Pollution* 302: 119046–119056. https://doi.org/10.1016/j.envpol.2022.119046.

Hamidian, A. H., E. J. Ozumchelouei, F. Feizi, C. Wu, Y. Zhang, and M. Yang. 2021. "A Review on the Characteristics of Microplastics in Wastewater Treatment Plants: A Source for Toxic Chemicals." *Journal of Cleaner Production* 295: 126480–126492. https://doi.org/10.1016/j.jclepro.2021.126480.

Huang, F., J. Hu, L. Chen, et al. 2023. "Microplastics May Increase the Environmental Risks of Cd via Promoting Cd Uptake by Plants: A Meta-analysis." *Journal of Hazardous Materials* 448: 130887–130898. https://doi.org/10.1016/j.jhazmat.2023.130887.

Huang, S., P. Wang, N. Yamaji, and J. F. Ma. 2020. "Plant Nutrition for Human Nutrition: Hints From Rice Research and Future Perspectives."

Molecular Plant 13, no. 6: 825–835. https://doi.org/10.1016/j.molp.2020.05.007.

Igalavithana, A. D., M. G. Y. L. Mahagamage, P. Gajanayake, et al. 2022. "Microplastics and Potentially Toxic Elements: Potential Human Exposure Pathways Through Agricultural Lands and Policy Based Countermeasures." *Microplastics* 1, no. 1: 102–120. https://doi.org/10.3390/microplastics1010007.

Iswahyudi, I., W. Widodo, W. Warkoyo, A. Sutanto, M. P. Garfansa, and E. D. Septia. 2024. "Determination and Quantification of Microplastics in Compost." *Environmental Quality Management* 35, no. 1: 22184–22194. https://doi.org/10.1002/tqem.22184.

Junaid, M., J. A. Siddiqui, M. Sadaf, S. Liu, and J. Wang. 2022. "Enrichment and Dissemination of Bacterial Pathogens by Microplastics in the Aquatic Environment." *Science of the Total Environment* 830: 154720–154732. https://doi.org/10.1016/j.scitotenv.2022.154720.

Junhao, C., Z. Xining, G. Xiaodong, Z. Li, H. Qi, and K. H. M. Siddique. 2021. "Extraction and Identification Methods of Microplastics and Nanoplastics in Agricultural Soil: A Review." *Journal of Environmental Management* 294: 112997–113011. https://doi.org/10.1016/j.jenvman.2021.112997.

Kamal, A., F. Ahmad, and M. A. Shafeeque. 2020. "Toxicity of Pesticides to Plants and Non-target Organism: A Comprehensive Review." *Iranian Journal of Plant Physiology* 10, no. 4: 3299–3313. https://doi.org/10.30495/ijpp.2020.1885628.1183.

Li, J., Y. Yu, Z. Zhang, and M. Cui. 2023a. "The Positive Effects of Polypropylene and Polyvinyl Chloride Microplastics on Agricultural Soil Quality." *Journal of Soils and Sediments* 23, no. 3: 1304–1314. https://doi.org/10.1007/s11368-022-03387-6.

Li, Z., X. Zeng, F. Sun, et al. 2023b. "Physiological Analysis and Transcriptome Profiling Reveals the Impact of Microplastic on Melon (Cucumis melo L.) Seed Germination and Seedling Growth." *Journal of Plant Physiology* 287: 154039–154049. https://doi.org/10.1016/j.jplph.2023.154039.

Lian, J., J. Wu, H. Xiong, et al. 2020. "Impact of Polystyrene Nanoplastics (PSNPs) on Seed Germination and Seedling Growth of Wheat (Triticum aestivum L.)." *Journal of Hazardous Materials* 385: 121620–121630. https://doi.org/10.1016/j.jhazmat.2019.121620.

Lichtenthaler, H. K., and C. Buschmann. 2001. "Chlorophylls and Carotenoids: Measurement and Characterization by UV-VIS Spectroscopy." *Current Protocols in Food Analytical Chemistry* 1, no. 1: F4.3.1–F4.3.8. https://doi.org/10.1002/0471142913.faf0403s01.

Liu, S., J. Wang, J. Zhu, J. Wang, H. Wang, and X. Zhan. 2021. "The Joint Toxicity of Polyethylene Microplastic and Phenanthrene to Wheat Seedlings." *Chemosphere* 282: 130967–130978. https://doi.org/10.1016/j.chemosphere.2021.130967.

Liu, S. L., M. F. Jian, L. Y. Zhou, W. H. Li, X. E. Wu, and D. Rao. 2019. "Pollution Characteristics of Microplastics in Migratory Bird Habitats Located Within Poyang Lake Wetlands." *Huanjing Kexue/Environmental Science* 40, no. 6: 2639–2646. https://doi.org/10.13227/j.hjkx.201812111.

Mamun, A. A., T. A. E. Prasetya, I. R. Dewi, and M. Ahmad. 2023. "Microplastics in Human Food Chains: Food Becoming a Threat to Health Safety." *Science of the Total Environment* 858: 159834–159844. https://doi.org/10.1016/j.scitotenv.2022.159834.

Masud, A. A., A. R. M. T. Islam, A. A. Mamun, et al. 2024. "A New Approach From Public Behavioral Attitudes and Perceptions Towards Microplastics: Influencing Factors, and Policy Proposals." *Ocean & Coastal Management* 253: 107144–107157. https://doi.org/10.1016/j.ocecoaman.2024.107144.

Nagajyoti, P. C., K. D. Lee, and T. V. M. Sreekanth. 2010. "Heavy Metals, Occurrence and Toxicity for Plants: A Review." *Environmental Chemistry Letters* 8, no. 3: 199–216. https://doi.org/10.1007/s10311-010-0297-8.

Prata, J. C., J. P. da Costa, I. Lopes, A. C. Duarte, and T. Rocha-Santos. 2020. "Environmental Exposure to Microplastics: An Overview on Possible Human Health Effects." *Science of the Total Environment* 702: 134455–134468. https://doi.org/10.1016/j.scitotenv.2019.134455.

Qi, Y., X. Yang, A. M. Pelaez, et al. 2018. "Macro- and Micro- Plastics in Soil-Plant System: Effects of Plastic Mulch Film Residues on Wheat (Triticum aestivum) Growth." *Science of the Total Environment* 645: 1048–1056. https://doi.org/10.1016/j.scitotenv.2018.07.229.

Rillig, M. C., A. Lehmann, A. A. de Souza Machado, and G. Yang. 2019. "Microplastic Effects on Plants." *New Phytologist* 223, no. 3: 1066–1070. https://doi.org/10.1111/nph.15794.

Riyazuddin, R., N. Nisha, B. Ejaz, et al. 2022. "A Comprehensive Review on the Heavy Metal Toxicity and Sequestration in Plants." *Biomolecules* 12, no. 1: 43–56. https://doi.org/10.3390/biom12010043.

Sahasa, R. G. K., P. Dhevagi, R. Poornima, et al. 2023. "Effect of Polyethylene Microplastics on Seed Germination of Blackgram (Vigna mungo L.) and Tomato (Solanum lycopersicum L.)." *Environmental Advances* 11: 100349–100360. https://doi.org/10.1016/j.envadv.2023.100349.

Sathish, T., N. Sabarirajan, S. Ravichandran, G. M. Moorthy, and S. Dinesh kumar. 2022. "Novel Study on Improvement of Plastics Properties by Blending of Waste Micro Plastics into ABS Plastics." *Chemosphere* 303: 134997–135009. https://doi.org/10.1016/j.chemosphere.2022.134997.

Sembiring, E., A. A. Fareza, V. Suendo, and M. Reza. 2020. "The Presence of Microplastics in Water, Sediment, and Milkfish (chanos chanos) at the Downstream Area of Citarum River, Indonesia." *Water, Air, & Soil Pollution* 231, no. 7: 355–369. https://doi.org/10.1007/s11270-020-04710-y.

Shruti, V. C., M. P. Jonathan, P. F. Rodriguez-Espinosa, and F. Rodríguez-González. 2019. "Microplastics in Freshwater Sediments of Atoyac River Basin, Puebla City, Mexico." *Science of the Total Environment* 654: 154–163. https://doi.org/10.1016/j.scitotenv.2018.11.054.

Silva, G. C., F. M. Galleguillos Madrid, D. Hernández, et al. 2021. "Microplastics and Their Effect in Horticultural Crops: Food Safety and Plant Stress." *Agronomy* 11, no. 8: 1528–1541. https://doi.org/10.3390/agronomy11081528.

Sobiechowska-Sasim, M., J. Stoń-Egiert, and A. Kosakowska. 2014. "Quantitative Analysis of Extracted Phycobilin Pigments in Cyanobacteria—An Assessment of Spectrophotometric and Spectrofluorometric Methods." *Journal of Applied Phycology* 26, no. 5: 2065–2074. https://doi.org/10.1007/s10811-014-0244-3.

Sun, H., Y. Shi, P. Zhao, et al. 2023. "Effects of Polyethylene and Biodegradable Microplastics on Photosynthesis, Antioxidant Defense Systems, and Arsenic Accumulation in Maize (Zea mays L.) Seedlings Grown in Arsenic-Contaminated Soils." *Science of the Total Environment* 868: 161557–161569. https://doi.org/10.1016/j.scitotenv.2023.161557.

Takagi, D., S. Takumi, M. Hashiguchi, T. Sejima, and C. Miyake. 2016. "Superoxide and Singlet Oxygen Produced Within the Thylakoid Membranes Both Cause Photosystem i Photoinhibition." *Plant Physiology* 171, no. 3: 1626–1634. https://doi.org/10.1104/pp.16.00246.

Thoma, M. V., N. Rohleder, and S. L. Rohner. 2021. "Clinical Ecopsychology: The Mental Health Impacts and Underlying Pathways of the Climate and Environmental Crisis." *Frontiers in Psychiatry* 12, no. 1: 3389–3400. https://doi.org/10.3389/fpsyt.2021.675936.

Ullah, R., M. T.-K. Tsui, H. Chen, A. Chow, C. Williams, and A. Ligaba-Osena. 2021. "Microplastics Interaction With Terrestrial Plants and Their Impacts on Agriculture." *Journal of Environmental Quality* 50, no. 5: 1024–1041. https://doi.org/10.1002/jeq2.20264.

Wang, F., X. Zhang, S. Zhang, S. Zhang, C. A. Adams, and Y. Sun. 2020a. "Effects of Co-Contamination of Microplastics and Cd on Plant Growth and Cd Accumulation." *Toxics* 8, no. 2: 36–51. https://doi.org/10.3390/toxics8020036.

Wang, J., T. Chen, W. Zhang, Y. Zhao, S. Yang, and A. Chen. 2020b. "Tracing the Geographical Origin of Rice by Stable Isotopic Analyses Combined With Chemometrics." *Food Chemistry* 313: 126093–126103. https://doi.org/10.1016/j.foodchem.2019.126093.

Wu, P., S. Lin, G. Cao, et al. 2022. "Absorption, Distribution, Metabolism, Excretion and Toxicity of Microplastics in the human Body and Health Implications." *Journal of Hazardous Materials* 437: 129361–129372. https://doi.org/10.1016/j.jhazmat.2022.129361.

Yang, W., P. Cheng, C. A. Adams, et al. 2021. "Effects of Microplastics on Plant Growth and Arbuscular Mycorrhizal Fungal Communities in a Soil Spiked With ZnO Nanoparticles." *Soil Biology and Biochemistry* 155: 108179–108190. https://doi.org/10.1016/j.soilbio.2021.108179.

Yu, Y., J. Li, Y. Song, et al. 2022. "Stimulation Versus Inhibition: The Effect of Microplastics on Pak Choi Growth." *Applied Soil Ecology* 177: 104505–104521. https://doi.org/10.1016/j.apsoil.2022.104505.

Yuan, Y., M. Zu, R. Li, J. Zuo, and J. Tao. 2023. "Soil Properties, Microbial Diversity, and Changes in the Functionality of Saline-Alkali Soil are Driven by Microplastics." *Journal of Hazardous Materials* 446: 130712–130724. https://doi.org/10.1016/j.jhazmat.2022.130712.

Zhang, D., E. L. Ng, W. Hu, et al. 2020. "Plastic Pollution in Croplands Threatens Long-Term Food Security." *Global Change Biology* 26, no. 6: 3356–3367. https://doi.org/10.1111/gcb.15043.

Zhang, L., Y. Xie, S. Zhong, J. Liu, Y. Qin, and P. Gao. 2021. "Microplastics in Freshwater and Wild Fishes From Lijiang River in Guangxi, Southwest China." *Science of the Total Environment* 755: 142428–142440. https://doi.org/10.1016/j.scitotenv.2020.142428.

Zhou, C. Q., C. H. Lu, L. Mai, L. J. Bao, L. Y. Liu, and E. Y. Zeng. 2021. "Response of Rice (Oryza sativa L.) Roots to Nanoplastic Treatment at Seedling Stage." *Journal of Hazardous Materials* 401: 123412–123424. https://doi.org/10.1016/j.jhazmat.2020.123412.

Zhou, Y., X. Ren, T.-H. Tsui, et al. 2023. "Microplastics as an Underestimated Emerging Contaminant in Solid Organic Waste and Their Biological Products: Occurrence, Fate and Ecological Risks." *Journal of Hazardous Materials* 445: 130596–130608. https://doi.org/10.1016/j.jhazmat.2022.130596.

Zhu, J., Z. Zou, Y. Shen, et al. 2019. "Increased ZnO Nanoparticle Toxicity to Wheat Upon Co-Exposure to Phenanthrene." *Environmental Pollution* 247: 108–117. https://doi.org/10.1016/j.envpol.2019.01.046.