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Physiological and Biochemical Responses of Tomato (*Solanum lycopersicum* L.) to Polyethylene Microplastic Exposure

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ABSTRACT: Microplastics (MPs) are emerging environmental pollutants with potential impacts on terrestrial ecosystems and crop productivity. This study examined the effects of polyethylene microplastics (PE-MPs) on the physiological and biochemical responses of tomato (*Solanum lycopersicum* L.) plants under controlled greenhouse conditions. A completely randomized design was employed with soil treatments containing 0%, 1%, 3%, and 5% (w/w) MPs, each replicated five times. Tomato seeds were grown in MP-amended soils for six weeks under uniform environmental conditions, after which growth parameters, photosynthetic pigments (chlorophyll a, chlorophyll b, and total chlorophyll), antioxidant enzyme activities (superoxide dismutase, catalase, and peroxidase), and stress biomarkers (malondialdehyde, MDA) were assessed using standard analytical procedures. Increasing MP concentrations significantly reduced plant growth, with shoot height declining from 47.6 cm in the control to 30.1 cm at 5% MPs, root length decreasing from 18.4 cm to 10.7 cm, and dry biomass decreasing from 3.25 g to 1.98 g. Total chlorophyll content declined from 2.56 to 1.51 mg g⁻¹ FW, indicating impaired photosynthetic capacity. In contrast, antioxidant enzyme activities increased markedly, with SOD, CAT, and POD reaching approximately 172%, 165%, and 159% of control levels, respectively, while MDA content increased by approximately 2.3-fold, confirming enhanced lipid peroxidation and oxidative stress. Overall, MPs caused dose-dependent toxicity by disrupting plant growth, impairing photosynthesis, and inducing oxidative stress, highlighting potential risks to crop productivity, soil health, and food security.

Keywords: microplastics; oxidative stress; antioxidant enzymes; photosynthetic pigments; plant physiology.

INTRODUCTION

Microplastics (MPs), defined as plastic particles smaller than 5 mm, have emerged as a widespread contaminant across aquatic and terrestrial ecosystems (Bläsing & Amelung, 2018; Boots et al., 2019). Conceptually, MPs constitute a novel class of abiotic stressors that interact with plants through physical and biochemical pathways. In soils, MPs can alter structure, porosity, and water dynamics, thereby affecting root growth and resource acquisition (Machado et al., 2019; de Souza Machado et al., 2019). At the same time, their surfaces can adsorb and transport chemical contaminants, potentially triggering cellular stress responses in plant tissues (Huang et al., 2019). This dual role places MPs within the broader theoretical framework of plant stress physiology, in which external environmental factors disrupt homeostasis and elicit adaptive or damaging responses (Gill & Tuteja, 2010). While early research focused primarily on marine systems, growing evidence suggests that MPs may significantly influence soil–plant interactions, with implications for nutrient cycling, crop performance, and ecosystem functioning (Boots et al., 2019; de Oliveira & Barbosa, 2021).

This study, therefore, investigates the effects of different concentrations of polyethylene microplastics on the growth, photosynthetic pigments, and antioxidant enzyme activities of tomato plants under controlled conditions. By elucidating the physiological and biochemical responses of tomatoes to microplastic exposure, this research provides valuable insights into the emerging field of plant–microplastic interactions as conceptualized in (Fig. 1).

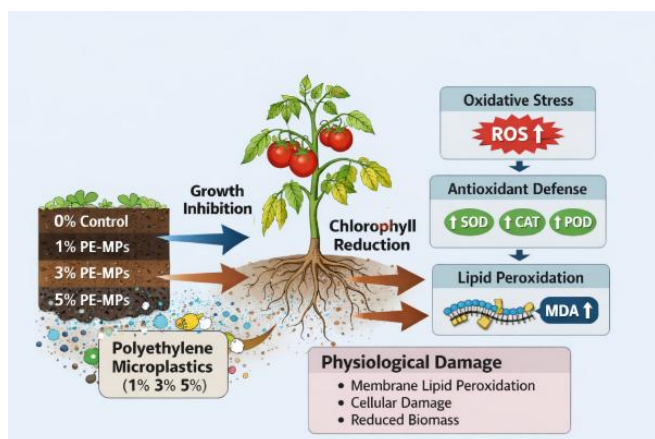


Fig. 1. Conceptual framework illustrating the effects of polyethylene microplastics on soil properties and plant physiological responses.

Microplastics alter soil structure and induce reactive oxygen species (ROS) generation, leading to reduced growth and chlorophyll content, and increased antioxidant enzyme activity and lipid peroxidation in tomato plants.

MATERIALS AND METHODS

2.1 Experimental Site and Design

The experiment was conducted in the Department of Plant Biology, University of Ilorin, Nigeria (8°29'N, 4°40'E), under greenhouse conditions. The study employed a completely randomized design (CRD) with four treatments and five replicates per treatment. Treatments consisted of polyethylene microplastics (PE-MPs) at different concentrations (0%, 1%, 3%, and 5% w/w) mixed with soil. Each experimental unit contained 5 kg of homogenized loamy soil thoroughly mixed with the designated MP concentration.

2.2 Plant Material and Growth Conditions

Tomato (*Solanum lycopersicum* L.) seeds of a uniform commercial variety were surface-sterilized using 5% sodium hypochlorite for 2 minutes, rinsed with distilled water, and sown in prepared pots. After germination, seedlings were thinned to one plant per pot. Plants were maintained under natural light conditions (12h photoperiod), at an average temperature of $28 \pm 2^\circ\text{C}$, and watered daily to maintain field capacity throughout the experiment. No additional fertilizers or growth stimulants were applied to isolate the effects of microplastic exposure.

2.3 Microplastic Preparation

Polyethylene (PE) microplastics were derived from commercially available plastic films. The plastics were mechanically ground and sieved to obtain particle sizes between 1 and 5 mm in diameter. The prepared MPs were cleaned with distilled water, oven-dried at 60°C for 24 hours, and weighed accurately before the soil incorporation. The 1%,

3%, and 5% w/w concentrations were calculated based on total soil weight.

2.4 Growth Parameter Assessment

After six weeks of cultivation, plants were carefully uprooted and washed with distilled water. Morphological parameters, including shoot height (cm), root length (cm), number of leaves, and leaf area (cm^2), were measured. Fresh and dry biomass were determined using a digital weighing balance after oven-drying samples at 70°C for 48 hours until constant weight was achieved.

2.5 Photosynthetic Pigment Analysis

Chlorophyll *a*, chlorophyll *b*, and total chlorophyll were quantified using the method of Arnon (1949). Fresh leaf tissue (0.5 g) was homogenized in 80% acetone and centrifuged at 5,000 rpm for 10 minutes. The absorbance of the supernatant was measured at 645 nm and 663 nm using a UV-visible spectrophotometer (Model 752N, Shanghai Spectrum Instruments, China). Pigment concentrations were calculated using standard equations and expressed as mg g^{-1} fresh weight (FW).

2.6 Determination of Antioxidant Enzyme Activities

Enzymatic activities were determined from fresh leaf extracts prepared in 50 mM phosphate buffer (pH 7.0) and centrifuged at 10,000 rpm for 15 minutes at 4°C .

- Catalase (CAT) activity was assayed by monitoring the decomposition of H_2O_2 at 240 nm following the method of Aebi (1984).
- Superoxide dismutase (SOD) activity was determined by its ability to inhibit nitroblue tetrazolium (NBT) reduction at 560 nm as described by Beauchamp and Fridovich (1971).
- Peroxidase (POD) activity was measured according to Chance and Maehly (1955) by recording the oxidation of guaiacol at 470 nm. All enzyme activities were expressed in units (U mg^{-1} protein), where one unit corresponds to the change in absorbance per minute under assay conditions.

2.7 Lipid Peroxidation (MDA Content)

Lipid peroxidation was assessed by measuring malondialdehyde (MDA) content as an index of oxidative damage using the thiobarbituric acid (TBA) method described by Heath and Packer (1968). Fresh leaf tissue (0.5 g) was homogenized in 0.1% trichloroacetic acid (TCA) and centrifuged at 10,000 rpm for 10 minutes. The supernatant (1 mL) was mixed with 4 mL of 0.5% TBA in 20% TCA and heated at 95°C for 30 minutes, then quickly cooled on ice.

Absorbance was read at 532 nm and corrected for nonspecific turbidity at 600 nm. MDA concentration was calculated using the extinction coefficient of 155 mM⁻¹ cm⁻¹.

2.8 Statistical Analysis

All data were subjected to statistical analyses using IBM SPSS Statistics version 25.0. Results were expressed as mean ± standard error (SE). One-way analysis of variance (ANOVA) was used to test for significant differences among treatment means, and separation of means was performed using Tukey’s Honestly Significant Difference (HSD) test at p < 0.05.

RESULTS AND DISCUSSIONS

3.1 Effects of Microplastic Concentration on Growth Parameters

Microplastic (MP) exposure caused a dose-dependent reduction in tomato plant growth (Table 1). Significant decreases in shoot height, root length, leaf number, and biomass were observed with increasing MP concentration (Fig. 2). Plants grown in soils containing 1%, 3%, and 5% polyethylene microplastics (PE-MPs) exhibited significant (p < 0.05) decreases in shoot height, root length, and leaf number compared with the control. The reduction was most pronounced at 5% MP concentration, where mean shoot height declined by approximately 37%, and root length by 42% relative to untreated plants. Leaf area followed a similar trend, decreasing progressively as MP concentration increased. Dry biomass accumulation also declined significantly with MP exposure, confirming inhibitory effects on overall plant productivity.

Table 1. Effects of polyethylene microplastic concentrations on growth parameters of tomato (*Solanum lycopersicum* L.).

Treatment (% MPs w/w)	Shoot height (cm)	Root length (cm)	No. of leaves	Leaf area (cm ²)	Dry biomass (g)	
0 (Control)	47.6 ± 18.4 1.2 a	± 18.4 0.6 a	± 12.0 0.4 a	± 38.7 0.8 a	± 3.25 0.07 a	±
1	41.2 ± 15.6 1.1 b	± 15.6 0.7 b	± 10.6 0.5 b	± 32.1 0.9 b	± 2.81 0.06 b	±
3	35.5 ± 13.2 1.3 c	± 13.2 0.5 c	± 9.0 0.3 c	± 28.6 1.0 c	± 2.44 0.04 c	±
5	30.1 ± 10.7 0.9 d	± 10.7 0.4 d	± 7.5 0.4 d	± 24.3 0.8 d	± 1.98 0.05 d	±

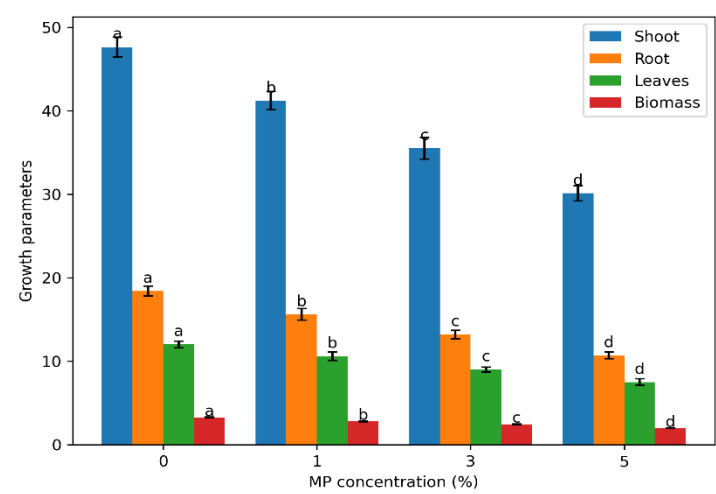


Fig. 2. Effects of polyethylene microplastic exposure on physiological and biochemical responses of tomato (*Solanum lycopersicum* L.).
 (A) Growth parameters (shoot height, root length, leaf number, and biomass).
 (B) Chlorophyll content (chlorophyll a, chlorophyll b, and total chlorophyll).
 (C) Relative antioxidant enzyme activities (SOD, CAT, and POD), expressed as percentage of control.
 (D) Malondialdehyde (MDA) content indicating lipid peroxidation.
 Values represent mean ± SE (n = 5). Different letters indicate significant differences at p < 0.05.

3.2 Photosynthetic Pigment Content

Polyethylene MPs significantly reduced chlorophyll pigment content (Table 2). Chlorophyll a, chlorophyll b, and total chlorophyll content decreased progressively with increasing microplastic concentration, indicating impaired photosynthetic capacity (Fig. 3). This suggests interference with photosynthetic machinery and pigment biosynthesis. The chlorophyll a/b ratio remained relatively stable, indicating proportionate decreases in both pigments.

Table 2. Effect of microplastic concentration on photosynthetic pigment content (mg g⁻¹ FW) of tomato leaves.

Treatment (% MPs w/w)	Chlorophyll a	Chlorophyll b	Total chlorophyll
0 (Control)	1.68 ± 0.04 a	0.88 ± 0.03 a	2.56 ± 0.06 a
1	1.47 ± 0.05 b	0.75 ± 0.04 b	2.22 ± 0.05 b
3	1.28 ± 0.03 c	0.64 ± 0.02 c	1.92 ± 0.04 c

Treatment (MPs w/w)	% Chlorophyll <i>a</i>	Chlorophyll <i>b</i>	Total chlorophyll
5	1.02 ± 0.04 d	0.49 ± 0.03 d	1.51 ± 0.05 d

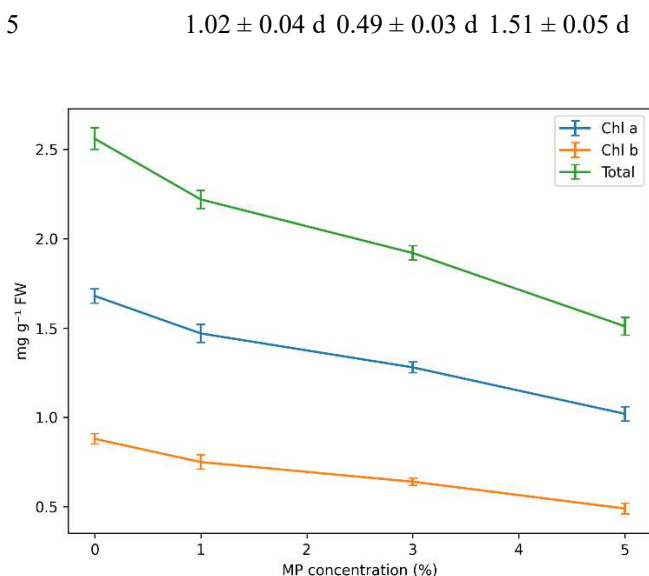


Fig 3. Changes in chlorophyll pigments (*a*, *b*, total) in tomato leaves under different polyethylene microplastic concentrations.

3.3 Antioxidant Enzyme Activities

Antioxidant enzyme activities increased progressively with microplastic concentration, reaching maximum levels at 5% MPs. When expressed relative to the control (100%), SOD, CAT, and POD activities increased to approximately 172%, 165%, and 159%, respectively (Fig. 4). The upregulation of these enzymes indicates an active oxidative stress defense mechanism triggered by MP-induced accumulation of reactive oxygen species (ROS).

Relative antioxidant enzyme activities (superoxide dismutase, catalase, and peroxidase) in tomato leaves exposed to increasing concentrations of polyethylene microplastics. Values are expressed as a percentage of control (0% MPs = 100%). Error bars represent standard error ($n = 5$). Different letters indicate significant differences at $p < 0.05$.

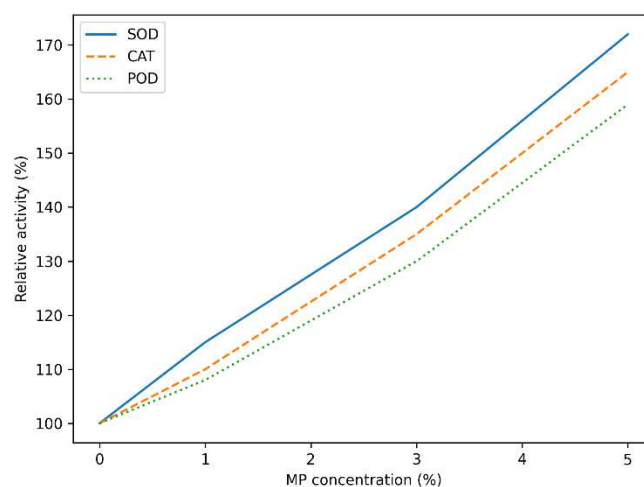


Figure 4. Antioxidant enzyme activities (SOD, CAT, POD) in tomato leaves exposed to increasing concentrations of polyethylene microplastics

3.4 Lipid Peroxidation (MDA Content)

Malondialdehyde (MDA) content increased progressively with higher microplastic concentrations, indicating enhanced lipid peroxidation and membrane damage (Fig. 5). The 5% MP treatment recorded the highest MDA value, approximately 2.3-fold higher than the control, confirming elevated oxidative membrane damage in response to MP stress. Figure 2 shows the effect of microplastic concentration on malondialdehyde (MDA) content in tomato leaves. Values are means $\pm$ SE ($n = 5$). Different letters denote significant differences ($p < 0.05$).

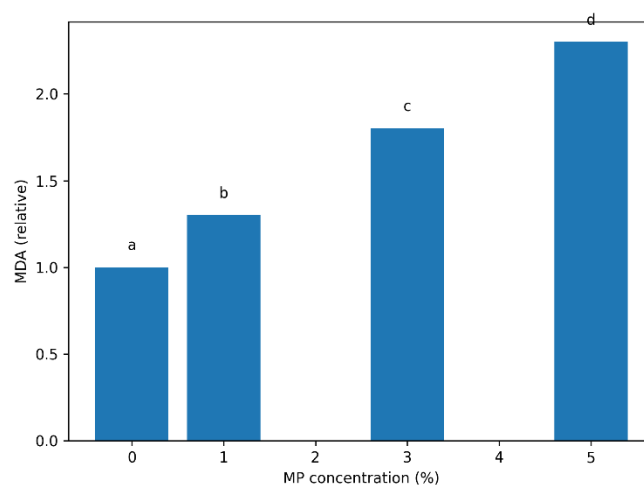


Fig 5. Malondialdehyde (MDA) content in tomato leaves as an indicator of lipid peroxidation under polyethylene microplastic stress.

3.5 Summary of Physiological and Biochemical Responses

The overall physiological and biochemical responses of tomato plants to microplastic exposure are summarized schematically (Fig. 6). These findings collectively indicate that MP exposure disrupts normal plant metabolism, leading to physiological stress and oxidative imbalance.

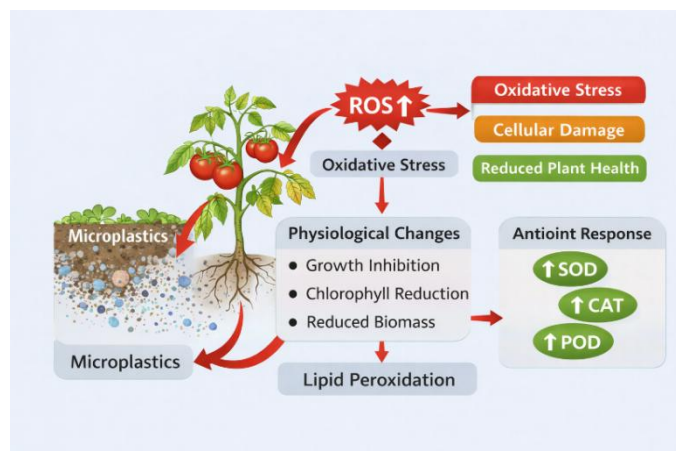


Fig 6. Schematic summary of the physiological and biochemical impacts of polyethylene microplastics on tomato plants.

DISCUSSION

This study demonstrated that polyethylene microplastics (PE-MPs) significantly impaired the growth, photosynthetic performance, and biochemical stability of tomato (*Solanum lycopersicum* L.) plants in a concentration-dependent manner. The observed reductions in shoot and root length, leaf area, and biomass are consistent with earlier findings that soil microplastics can alter soil physical structure and restrict plant development (Bläsing & Amelung, 2018; Boots et al., 2019). High microplastic concentrations have been shown to reduce soil porosity and water-holding capacity, thereby limiting oxygen diffusion and root penetration (Machado et al., 2019). These physical alterations likely contributed to the stunted growth and reduced biomass accumulation recorded at higher MP concentrations in this study.

The decline in chlorophyll *a*, *b*, and total chlorophyll content further indicates disruption of photosynthetic processes. Similar declines have been reported in lettuce, wheat, and cucumber exposed to polyethylene and polystyrene MPs (de Souza Machado et al., 2019; Dong et al., 2021). The reduction in chlorophyll content may be attributed to either inhibition of chlorophyll biosynthetic enzymes or enhanced degradation due to oxidative stress (de Oliveira & Barbosa, 2021). Microplastics can adsorb and transport toxic additives or heavy metals, increasing the oxidative burden within plant tissues (Gill & Tuteja, 2010). Consequently, the observed reduction in pigment content suggests that MPs interfere not only with carbon assimilation but also with photochemical efficiency, which ultimately constrains plant growth and productivity.

A major finding of this study was the significant increase in antioxidant enzyme activities superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD) in MP-treated plants. These enzymes constitute the first line of defense against reactive oxygen species (ROS), which are produced excessively under environmental stress (Gill & Tuteja, 2010). The enhanced activities observed here indicate that microplastic exposure triggers oxidative stress, prompting the activation of detoxifying pathways to maintain cellular homeostasis. Comparable results were obtained by Qi et al. (2018), who reported increased SOD and CAT activity in wheat roots exposed to microplastics. Elevated antioxidant activity represents an adaptive response that mitigates oxidative injury; however, under severe or prolonged stress, these protective mechanisms may become overwhelmed, resulting in cellular damage.

This hypothesis is supported by the increased malondialdehyde (MDA) content recorded in the present study, which reflects enhanced lipid peroxidation and membrane destabilization. MDA accumulation is a well-established marker of oxidative damage in plants subjected to abiotic stress (Lian et al., 2020; Jiang et al., 2019). The significant rise in MDA levels at 5% MP concentration suggests that the antioxidant defense was insufficient to fully counteract ROS toxicity. Similar findings have been documented in maize and rice subjected to plastic particle exposure, where excessive ROS led to degradation of membrane lipids and impaired metabolic function. Thus, it is plausible that the oxidative stress induced by MPs was a key factor in the physiological and biochemical disruptions observed (Lian et al., 2020; Jiang et al., 2019).

Beyond oxidative damage, MPs may also interfere with nutrient uptake and hormonal balance, indirectly influencing plant metabolism. For example, studies indicate that MPs can adsorb essential nutrients such as nitrate and phosphate, reducing their bioavailability to plants (Yu et al., 2019). Furthermore, microplastic-induced stress may alter phytohormone signaling particularly abscisic acid (ABA) and auxins thereby influencing growth regulation and stress adaptation pathways (Lehmann et al., 2019). Although this study did not directly assess hormonal responses, the pronounced reduction in growth parameters observed at higher MP concentrations suggests possible involvement of such regulatory mechanisms.

From an ecological and agricultural perspective, the findings highlight important implications. The widespread use of polyethylene mulching films, combined with improper disposal and plastic waste degradation, could progressively increase MP concentrations in agricultural soils. Such contamination poses risks to crop productivity, food quality, and soil ecological balance (de Souza Machado et al., 2018). The physiological disruptions identified here suggest that microplastic pollution could compromise the resilience of food crops to additional environmental stresses, including drought and nutrient limitation. Therefore, understanding plant responses to MPs is

essential for developing management practices and remediation strategies that safeguard crop health and soil sustainability.

In summary, the present study provides evidence that polyethylene microplastics induce oxidative stress in tomato plants, leading to impaired growth, chlorophyll degradation, and lipid peroxidation. These responses mirror typical plant reactions to abiotic stressors and underscore the emerging role of microplastics as an environmental pollutant affecting terrestrial ecosystems. Further studies involving molecular and transcriptomic analyses are recommended to identify the specific genes and pathways involved in plant defense responses to microplastic exposure.

CONCLUSION

This study demonstrated that polyethylene microplastics (PE-MPs) exert significant concentration-dependent effects on the physiological and biochemical performance of tomato (*Solanum lycopersicum* L.) plants. Increasing microplastic concentrations led to substantial reductions in shoot height, root length, leaf area, biomass accumulation, and chlorophyll content, indicating impaired growth and disrupted photosynthetic processes.

Exposure to PE-MPs also triggered pronounced oxidative stress responses, as evidenced by elevated activities of antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), along with increased malondialdehyde (MDA) accumulation. These findings suggest that microplastic contamination disturbs cellular homeostasis and induces membrane lipid peroxidation in tomato plants.

The results highlight the potential risks of microplastic accumulation in agricultural soils, particularly considering the widespread use of plastic materials in modern farming systems. Persistent microplastic contamination may negatively affect crop productivity, soil quality, and agricultural sustainability, thereby posing broader ecological and food security concerns.

Overall, this study contributes to the growing understanding of plant microplastic interactions and identifies polyethylene microplastics as an emerging abiotic stressor in terrestrial ecosystems. Future studies should focus on long-term field investigations, molecular mechanisms of plant defense responses, and sustainable strategies for reducing plastic contamination in agricultural environments.

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STATEMENTS AND DECLARATIONS

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Author's Contributions

- Marvellous Oluwatosin Kudabo conceptualized and experimented, analyzed the data, and prepared the original draft.
- Success Philip Olagbile contributed to manuscript writing, review, and editing.
- Gabriel Kehinde Olawepo supervised the study and reviewed the manuscript.
- Amos Oluwatobiloba Olagbile reviewed and edited the manuscript.
- All authors approved the final manuscript.

Ethics Approval

This study did not involve human participants or animals; therefore, ethical approval was not required.

Consent to Participate

Not applicable

Consent to Publish

All authors consent to the publication of this manuscript.

Competing Interests

The authors declare no competing interests.

Data Availability Statement

The datasets generated during this study are available from the corresponding author upon reasonable request.