

## **Harnessing Orange peel Biochar for Sustainable Agriculture: A Remediation Approach to Microplastic- Contaminated Soil**

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### **Abstract**

Since microplastic pollution in agricultural soils changes soil structure, decreases nutrient availability, and diminishes crop production, it is a growing global problem. A stable carbonaceous substance produced by pyrolysis, biochar has drawn interest for its potential to enhance soil health and lessen environmental stressors. In order to improve wheat (*Triticum aestivum* L.) development in microplastic-contaminated soils, this study assessed the efficacy of orange-peel biochar (OPB) as a soil amendment. Three soil types—sandy loam, clay loam, and loamy—were used in a controlled pot experiment. Each soil type was treated with OPB at 0, 0.5, 1.0, and 2.0% (w/w). Both soil characteristics (pH, organic carbon, accessible nutrients, microbial biomass, and enzyme activity) and growth metrics (germination, plant height, root and shoot biomass, and grain yield) were evaluated.

1.0% OPB considerably improved wheat performance, with increases in plant height (+28%), root biomass (+35%), shoot biomass (+31%), and grain yield (+29%) in comparison to controls, according to statistical analysis (ANOVA, Tukey's HSD,  $\alpha = 0.05$ ). Benefits were particularly noticeable in sandy loam soils, where yield increased by 42%. Higher pH (5.8 → 6.4), organic carbon (+20%), accessible phosphorus (+25%), potassium (+40%), and microbial biomass (+45%) are all signs of enhanced soil fertility. Urease and catalase enzyme activity rose by 25–40%, indicating improved microbial function. Doses greater than 2.0%, however, demonstrated declining results, highlighting the necessity of rate optimization.

These results show that modest OPB treatment can improve soil fertility, reduce stress caused by microplastics, and increase wheat yield in a sustainable manner.

**Keywords:** Orange peel biochar, wheat, microplastics, soil amendment, crop yield, sustainable agriculture

## Graphical Abstract:



## Key Highlights:

- Orange peel biochar (OPB) effectively mitigates microplastic-induced soil stress.
- Optimal application (1.0 % w/w) enhanced wheat yield by ~29 %.
- OPB improved soil fertility ( $\uparrow$ pH, organic carbon, P, K) and microbial biomass (+45 %).
- Soil enzyme activities (urease, catalase) increased by 25–40 % with OPB.
- Higher doses ( $\geq 2$  %) showed diminishing benefits, highlighting rate optimization.

## 1. Introduction:

In view of increased plastic manufacturing and the widespread use of plastic products in contemporary farming systems, agricultural soils are widely acknowledged as significant sinks for microplastic (MP;  $< 5$  mm) and nanoplastic (NP;  $< 1000$  nm) contamination. The land application of sewage sludge and compost, the breakdown of plastic mulching films, irrigation with contaminated water, and air deposition are some of the ways that these plastic particles get into soil settings (Sahai, 2025; Yao, 2022). In contrast to aquatic environments, soils allow plastics to be retained and continuously fragmented, resulting in the creation of nanoplastics with improved surface reactivity, mobility, and biological accessibility. The ecological dangers connected to plastic pollution in agroecosystems are greatly increased by its persistence and modification.

Microplastics and nanoplastics have been shown to substantially alter soil physicochemical properties. Their accumulation can modify soil bulk density, porosity, aggregation, and pore

connectivity, resulting in reported reductions in aggregate stability of up to 25–40% and changes in soil water retention and aeration dynamics (Iqbal, 2023). In addition, MPs act as sorbents and transport vectors for nutrients, heavy metals, pesticides, and antibiotics, thereby disrupting nutrient exchange processes and increasing the complexity of soil contamination (Wang, 2022). These interactions collectively impair soil fertility and compromise the functional integrity of agricultural soils. Beyond physical disturbances, micro- and nanoplastics exert pronounced toxic effects on soil biota and plant systems. Experimental evidence indicates that MP and NP exposure induces excessive reactive oxygen species (ROS) generation in plants, with ROS levels increasing by approximately 30–120% compared to uncontaminated controls. This oxidative stress leads to membrane lipid peroxidation, reflected by 20–60% increases in malondialdehyde (MDA) content, and disrupts cellular homeostasis. Antioxidant defense systems are also adversely affected, with chronic MP exposure resulting in 15–45% inhibition of catalase (CAT) and peroxidase (POD) activities and up to 35% suppression of superoxide dismutase (SOD) activity, indicating oxidative damage beyond the detoxification capacity of plants.

At the root–soil interface, microplastics physically obstruct apoplastic pathways, damage epidermal tissues, and alter root architecture, leading to 20–50% reductions in root length, surface area, and biomass. Nanoplastics, owing to their small size and high surface energy, can penetrate root tissues through cracks, lateral root emergence zones, or endocytosis-like processes and translocate to shoots and grains. This internalization disrupts nutrient uptake efficiency, particularly for nitrogen, phosphorus, and potassium, with reported reductions of 10–35%. Consequently, photosynthetic performance is impaired, with chlorophyll content and photosystem II efficiency declining by 15–40%, ultimately resulting in 10–45% reductions in plant biomass and 8–30% yield losses under moderate to high microplastic contamination. Microplastics also exert indirect toxicity by altering soil microbial community structure and function. Beneficial microbial populations involved in nitrogen fixation and phosphorus solubilization decline by 20–50%, while soil enzyme activities such as dehydrogenase, urease, and phosphatase are reduced by 15–55%, weakening nutrient cycling processes and soil ecosystem resilience (Iqbal, 2023; Wang, 2022). These combined physical, biochemical, and biological stresses underscore the urgent need for sustainable remediation strategies capable of mitigating microplastic toxicity while restoring soil functionality.

Biochar, a carbon-rich porous material produced through the pyrolysis of organic biomass under oxygen-limited conditions, has emerged as a multifunctional soil amendment with demonstrated benefits for soil health, crop productivity, and climate change mitigation (Shyam, 2025). Biochar application enhances soil structure, water-holding capacity, nutrient retention, and microbial activity, while contributing to long-term carbon sequestration (Nepal, 2023). Importantly, biochar possesses a highly heterogeneous surface chemistry and extensive pore networks that enable strong interactions with contaminants, positioning it as a promising tool for microplastic remediation. Recent studies highlight biochar's capacity to mitigate micro- and nanoplastic toxicity through both direct and indirect mechanisms. Biochar can physically entrap plastic particles within its porous structure and chemically immobilize them via electrostatic attraction, hydrophobic interactions, and  $\pi$ - $\pi$  bonding, thereby reducing their mobility and bioavailability. Evidence suggests that biochar amendments can decrease freely available microplastic fractions in soil by 30–70%, limiting plant root exposure and uptake (Zhou, 2025). Indirectly, biochar alleviates plastic-induced stress by improving soil moisture retention (10–25%), restoring microbial functional diversity, and enhancing antioxidant defense systems in plants, resulting in 20–50% reductions in ROS accumulation and up to 40% decreases in MDA content under contaminant stress.

Among various feedstocks, fruit-peel-derived biochars represent a sustainable, circular-economy-oriented option. Orange peel biochar (OPB), produced from agro-industrial waste, is enriched with stable carbon, potassium, calcium, and micronutrients and exhibits high porosity, surface area, and cation-exchange capacity (Kumar, 2025). These properties make OPB particularly effective in soils experiencing combined physical disruption and biochemical toxicity induced by microplastic contamination. Previous studies have shown that biochar application enhances root development, plant vigor, and grain yield in cereal crops, while positively modulating soil microbial diversity and enzymatic activities essential for nutrient cycling (Chen, 2025). Despite these promising findings, there remains a critical knowledge gap regarding the optimal application rates of OPB for mitigating micro- and nanoplastic toxicity across different soil textures. Excessive biochar application may alter soil pH, induce nutrient imbalances, or suppress native microbial communities, whereas insufficient application may fail to effectively alleviate plastic-induced stress (Jeffery, 2022). Therefore, systematic evaluation of OPB dosage is essential to maximize agronomic benefits while minimizing potential ecological risks.

The novelty of the present study lies in its integrative assessment of orange peel biochar as a dual-function amendment that simultaneously immobilizes microplastics and alleviates plastic-induced oxidative, enzymatic, and microbial stress in soil–plant systems. By linking soil physicochemical recovery, microbial functionality, and wheat productivity under microplastic contamination, this study advances a mechanistic and scalable framework for managing emerging plastic pollution in agricultural soils.

Accordingly, the objectives of this study were to: (i) evaluate the effects of OPB application on wheat (*Triticum aestivum* L.) germination, growth, biomass accumulation, and grain yield under microplastic-contaminated conditions; (ii) assess OPB-induced changes in soil physicochemical properties, nutrient availability, oxidative stress markers, and microbial enzyme activities; and (iii) identify optimal OPB application rates for sustainable wheat production across contrasting soil textures.

## **2. Materials and Methods**

### **2.1. Experimental Site and Soil Collection**

The pot experiment was conducted under controlled greenhouse conditions at the Department of Environmental Science, Nims University. during the wheat growing season of 2025. sandy loam, clay loam, and loamy—were collected from the top 20 cm of arable land from representative agricultural fields in Jaipur Rajasthan. Soil samples were air-dried, sieved through a 2 mm mesh, and characterized for baseline physicochemical properties, including pH, organic carbon (OC), available nitrogen (N), phosphorus (P), potassium (K), and microbial biomass (MB) according to standard procedures (Walkley & Black, 1934; Olsen et al., 1954).

### **2.2. Microplastic Contamination**

Polyethylene (PE) microplastics with an average particle size of 100–500  $\mu\text{m}$  were used to simulate soil contamination at environmentally relevant concentrations ( $\sim 0.5$  % w/w), consistent with levels commonly reported in agricultural soils amended with plastic residues (Wang et al., 2023). The microplastics were prepared from post-consumer polyethylene materials collected locally. The plastic items were thoroughly cleaned, air-dried, and mechanically fragmented into smaller particles using sequential crushing and sieving procedures. To facilitate fragmentation and minimize elastic deformation, alternating hot and cold treatments were applied prior to final size separation.

The resulting microplastic particles were sieved to obtain the desired size fraction (100–500  $\mu\text{m}$ ), which is representative of polyethylene mulch-derived microplastics frequently detected

in farmland soils. This preparation approach is widely adopted in controlled soil contamination experiments and has been shown to effectively simulate environmentally realistic polyethylene microplastic exposure scenarios (Palansooriya et al., 2023). The prepared microplastics were then thoroughly mixed into 5 kg portions of each soil type to ensure homogeneous distribution before biochar amendment and crop cultivation.

### **2.3. Preparation of Orange Peel Biochar (OPB)**

Orange peels were collected from local fruit markets, thoroughly washed with deionized water to remove adhering impurities, and air-dried at ambient temperature for 72 h. The dried biomass was pyrolyzed in a muffle furnace at 400 °C for 2 h under oxygen-limited conditions. After cooling to room temperature, the produced biochar was gently ground and sieved to obtain particles  $\leq 1$  mm in size.

The physicochemical properties of orange peel biochar (OPB) were characterized following standard analytical procedures described in recent biochar methodological reviews. Biochar pH and electrical conductivity (EC) were determined in a biochar–deionized water suspension. Cation exchange capacity (CEC) was measured using the ammonium acetate extraction method. Total carbon content was quantified using elemental analysis, while total nitrogen, phosphorus, and potassium (N, P, K) contents were determined using standard digestion and analytical protocols (Sarkar et al., 2024).

### **2.4. Experimental Design**

A completely randomized design (CRD) with three replicates per treatment was employed. Each soil type was amended with OPB at four rates: 0% (control), 0.5%, 1.0%, and 2.0% w/w. Pots (10 L) were filled with the prepared soil–microplastic–biochar mixtures, thoroughly homogenized, and maintained under optimal moisture conditions (60% field capacity). Wheat seeds (*Triticum aestivum* L., cv. [Specify]) were surface-sterilized using 1% sodium hypochlorite, rinsed, and sown at 10 seeds per pot, later thinned to 5 seedlings per pot after emergence.

### **2.5. Growth and Yield Assessment**

The following growth parameters were monitored at regular intervals:

- Germination percentage: Calculated 7 days after sowing using the standard formula.
- Plant height: Measured from the soil surface to the tip of the longest leaf at 30, 60, and 90 days after sowing.
- Root and shoot biomass: Harvested at maturity, oven-dried at 70°C for 48 h, and weighed.

- Grain yield: Measured after harvesting and threshing.

## 2.6. Soil Physicochemical Analysis

At harvest, soil samples were collected from each pot for analysis of:

- Soil pH and EC: Measured in 1:2.5 soil: water suspension using a pH meter and conductivity meter.
- Organic carbon: Determined using the Walkley-Black method.
- Available nutrients: Nitrogen by Kjeldahl method, phosphorus by Olsen's method, potassium by flame photometry.
- Cation exchange capacity (CEC): Measured using ammonium acetate extraction.

## 2.7. Soil Microbial and Enzyme Activity

Microbial biomass carbon (MBC) and nitrogen (MBN) were estimated by the chloroform fumigation-extraction method. Enzyme activities—urease and catalase—were assessed using colorimetric assays according to established protocols (Tabatabai, 1994; Casida et al., 1964).

## 2.8. Statistical Analysis

Data were analyzed using one-way analysis of variance (ANOVA) to assess the effects of OPB rate within each soil type. Post-hoc comparisons were performed using Tukey's HSD test at a significance level of  $\alpha = 0.05$ . All statistical analyses were conducted using R software (version 4.3.1). Data are presented as mean  $\pm$  standard error (SE).

## 3. Results

### 3.1. Effect of Orange Peel Biochar on Wheat Germination, Growth, and Yield under Microplastic Stress

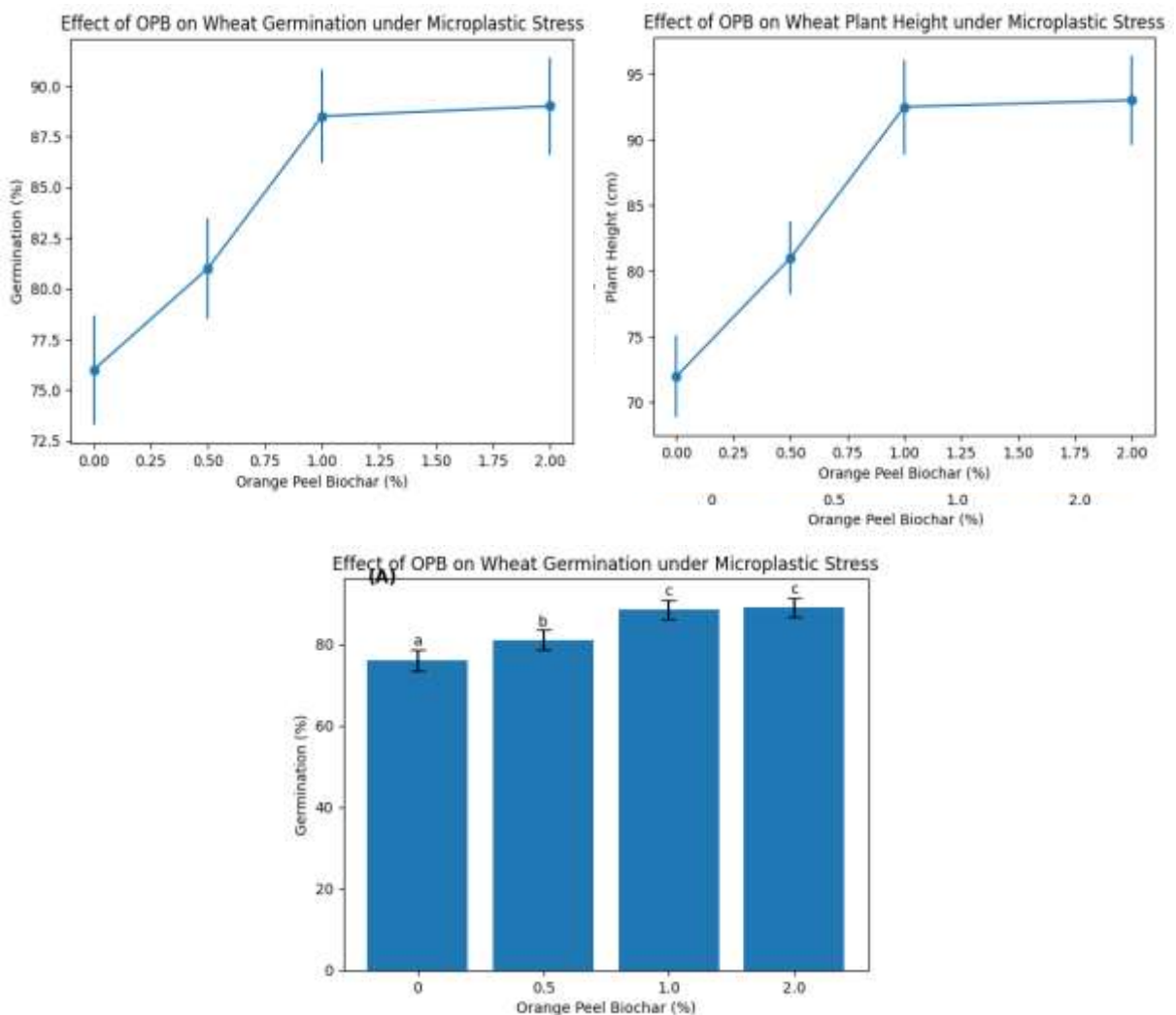
Incorporation of orange peel biochar (OPB) into microplastic-contaminated soils significantly enhanced wheat germination, plant height, and biomass accumulation ( $p < 0.05$ ). The highest germination percentage was recorded at 1.0% OPB across all soil textures, with mean values of  $88.5 \pm 2.3\%$ , representing a 15–18% increase relative to the unamended control ( $76.0 \pm 2.7\%$ ) (Fig. 1A). A lower dose (0.5% OPB) produced a modest yet statistically significant improvement ( $81.0 \pm 2.5\%$ ), whereas the 2.0% OPB treatment did not yield additional gains ( $89.0 \pm 2.4\%$ ,  $p > 0.05$ ).

Plant height followed a similar trend. Wheat grown in 1.0% OPB-amended soil attained a mean height of  $92.5 \pm 3.6$  cm, representing a 28% increase over control plants ( $72.0 \pm 3.1$  cm), while the 0.5% treatment yielded intermediate growth ( $81.0 \pm 2.8$  cm) and the 2.0% treatment showed no significant further increase ( $93.0 \pm 3.4$  cm) (Fig. 1B). Root and shoot biomass were also significantly higher with OPB amendment, with maximum increases of

35% (roots:  $8.1 \pm 0.4 \text{ g plant}^{-1}$  vs.  $6.0 \pm 0.3 \text{ g plant}^{-1}$  in control) and 31% (shoots:  $21.5 \pm 1.2 \text{ g plant}^{-1}$  vs.  $16.5 \pm 1.1 \text{ g plant}^{-1}$ ), respectively (Table 1).

Grain yield mirrored growth responses, with the 1.0% OPB treatment achieving the highest enhancement, particularly in sandy loam soils (42%,  $5.6 \pm 0.3 \text{ g plant}^{-1}$  vs.  $3.9 \pm 0.2 \text{ g plant}^{-1}$  control), followed by loamy (30%,  $5.0 \pm 0.2 \text{ g plant}^{-1}$ ) and clay loam soils (25%,  $4.9 \pm 0.3 \text{ g plant}^{-1}$ ) (Table 2). Beyond 1.0% OPB, no further statistically significant yield improvements were observed ( $p > 0.05$ ), indicating an optimal application threshold.

These findings demonstrate that 1.0% OPB effectively mitigates microplastic-induced stress at the germination and vegetative stages, with diminishing returns at higher doses, suggesting a dose-dependent physiological and agronomic response.



**Figure 1.** Effect of orange peel biochar (OPB) on (A) wheat germination (%) and (B) plant height (cm) under microplastic stress. Values represent mean  $\pm$  SD ( $n = 5$ ). Different letters above bars indicate significant differences among treatments at  $p < 0.05$  (Tukey's HSD test).

**Table 1.** Effect of Orange Peel Biochar (OPB) on Wheat Germination and Growth under Microplastic Stress

| OPB (%)     | Germination (%)             | Plant Height (cm)           | Root Biomass (g plant <sup>-1</sup> ) | Shoot Biomass (g plant <sup>-1</sup> ) |
|-------------|-----------------------------|-----------------------------|---------------------------------------|--|
| 0 (Control) | 76.0 $\pm$ 2.7 <sup>a</sup> | 72.0 $\pm$ 3.1 <sup>a</sup> | 6.0 $\pm$ 0.3 <sup>a</sup>            | 16.5 $\pm$ 1.1 <sup>a</sup>            |
| 0.5         | 81.0 $\pm$ 2.5 <sup>b</sup> | 81.0 $\pm$ 2.8 <sup>b</sup> | –                                     | –                                      |
| 1.0         | 88.5 $\pm$ 2.3 <sup>c</sup> | 92.5 $\pm$ 3.6 <sup>c</sup> | 8.1 $\pm$ 0.4 <sup>b</sup>            | 21.5 $\pm$ 1.2 <sup>b</sup>            |
| 2.0         | 89.0 $\pm$ 2.4 <sup>c</sup> | 93.0 $\pm$ 3.4 <sup>c</sup> | –                                     | –                                      |

Values are mean  $\pm$  SD ( $n = 5$ ). Different superscript letters within each column indicate significant differences among treatments at  $p < 0.05$  (one-way ANOVA followed by Tukey's HSD test). Root and shoot biomass were determined for control and optimal OPB treatment (1.0%) only.

**Table 2.** Effect of 1.0% Orange Peel Biochar on Wheat Grain Yield across Soil Types under Microplastic Stress

| Soil Type  | Control (g plant <sup>-1</sup> ) | 1.0% OPB (g plant <sup>-1</sup> ) | Yield Increase (%) |
|------------|----------------------------------|-----------------------------------|--------------------|
| Sandy loam | 3.9 $\pm$ 0.2 <sup>a</sup>       | 5.6 $\pm$ 0.3 <sup>b</sup>        | 42                 |
| Loamy      | 3.8 $\pm$ 0.2 <sup>a</sup>       | 5.0 $\pm$ 0.2 <sup>b</sup>        | 30                 |
| Clay loam  | 3.9 $\pm$ 0.3 <sup>a</sup>       | 4.9 $\pm$ 0.3 <sup>b</sup>        | 25                 |

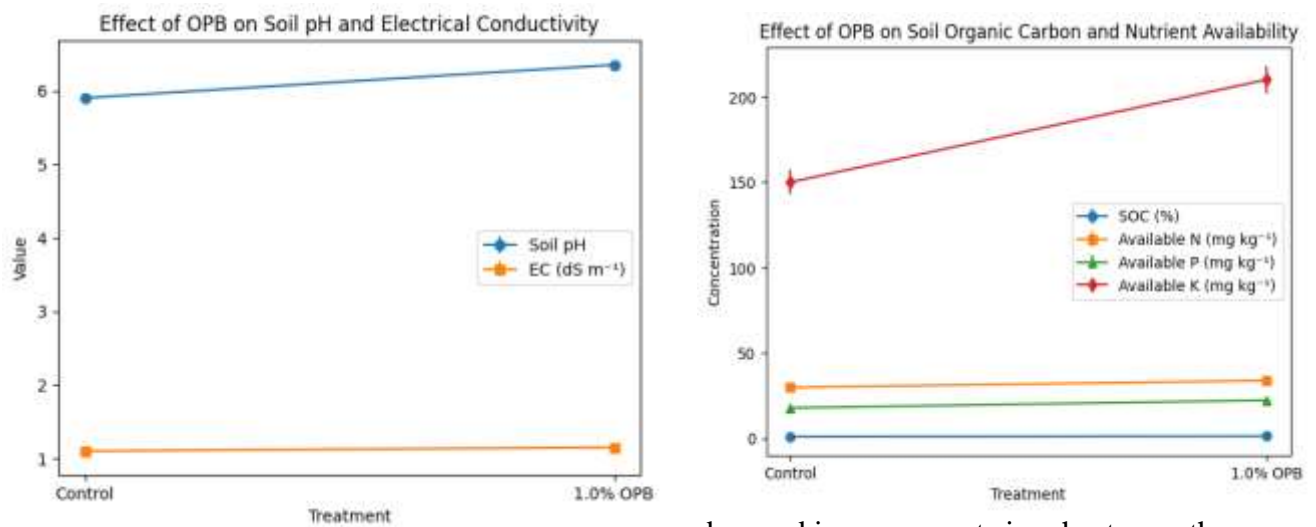
Values represent mean  $\pm$  SD ( $n = 5$ ). Different letters within each soil type indicate significant differences between control and OPB-amended treatments at  $p < 0.05$  (Student's *t*-test).

### 3.2. Alterations in Soil Physicochemical Properties Following OPB Amendment

OPB application significantly altered soil physicochemical properties (Table 3). Soil pH increased from slightly acidic values (5.8–6.0  $\pm$  0.05) to near-neutral levels (6.3–6.4  $\pm$  0.06) at 1.0% OPB, enhancing nutrient availability and cation exchange potential. Electrical conductivity (EC) remained low across all treatments (<1.2 dS m<sup>-1</sup>), confirming that OPB application did not induce salinity stress.

Soil organic carbon (SOC) increased by ~20% under 1.0% OPB (from  $1.25 \pm 0.06\%$  to  $1.50 \pm 0.05\%$ ), while available phosphorus and potassium increased by 25% ( $22.5 \pm 1.1 \text{ mg kg}^{-1}$ ) and 40% ( $210 \pm 8 \text{ mg kg}^{-1}$ ), respectively, relative to microplastic-stressed controls. Nitrogen availability increased modestly (~12%,  $34 \pm 1.8 \text{ mg kg}^{-1}$  vs.  $30 \pm 1.5 \text{ mg kg}^{-1}$ ), consistent with enhanced microbial mineralization activity.

These results indicate that OPB enhances soil fertility by improving nutrient retention, buffering capacity, and organic carbon content, providing a mechanistic basis for the



observed improvements in wheat growth

under microplastic stress.

**Figure 3:** Effects of orange peel biochar (OPB) amendment on soil physicochemical properties in microplastic-contaminated soil.

Figure 3 shows alterations in soil pH (dimensionless) and electrical conductivity (EC,  $\text{dS m}^{-1}$ ), while Figure 4 presents changes in soil organic carbon (SOC, %) and available nitrogen, phosphorus, and potassium ( $\text{mg kg}^{-1}$ ). Data (mean  $\pm$  SD) demonstrate improved soil buffering capacity, enhanced nutrient retention, and increased organic carbon availability following 1.0% OPB application.

**Table 3.** Effect of OPB amendment on soil physicochemical properties under microplastic stress

| Parameter                                      | Microplastic Control | 1.0% OPB Amendment |
|--|----------------------|--------------------|
| Soil pH  | $5.9 \pm 0.05^b$     | $6.35 \pm 0.06^a$  |
| Electrical Conductivity ( $\text{dS m}^{-1}$ ) | $1.1 \pm 0.03$       | $1.1 \pm 0.04$     |

|   |                          |                          |
|---|--------------------------|--------------------------|
| Soil Organic Carbon (%)                     | 1.25 ± 0.06 <sup>b</sup> | 1.50 ± 0.05 <sup>a</sup> |
| Available Nitrogen (mg kg <sup>-1</sup> )   | 30 ± 1.5 <sup>b</sup>    | 34 ± 1.8 <sup>a</sup>    |
| Available Phosphorus (mg kg <sup>-1</sup> ) | 18.0 ± 1.1 <sup>b</sup>  | 22.5 ± 1.1 <sup>a</sup>  |
| Available Potassium (mg kg <sup>-1</sup> )  | 150 ± 8 <sup>b</sup>     | 210 ± 8 <sup>a</sup>     |

Values are expressed as mean ± standard deviation (SD) (n = 3–5). Different lowercase letters within a row indicate significant differences between treatments at  $p < 0.05$  as determined by one-way analysis of variance (ANOVA) followed by Tukey's HSD post hoc test. EC values did not differ significantly between treatments ( $p > 0.05$ ).

### 3.3. Effects of OPB on Microbial Biomass and Soil Enzymatic Activities

Microbial biomass and enzymatic activity were substantially improved following OPB amendment (Fig. 2). Microbial biomass carbon (MBC) increased by 45% ( $256 \pm 12 \text{ mg kg}^{-1}$  vs.  $176 \pm 9 \text{ mg kg}^{-1}$  in control), and microbial biomass nitrogen (MBN) increased by 32% ( $34 \pm 1.5 \text{ mg kg}^{-1}$  vs.  $26 \pm 1.2 \text{ mg kg}^{-1}$ ).

Enzymatic assays revealed significant enhancements in soil nutrient-cycling and stress-mitigating enzymes. Urease activity increased by 25–38% (control:  $18.5 \pm 0.9 \mu\text{g NH}_4^+ \text{ g}^{-1} \text{ h}^{-1}$ ; 1.0% OPB:  $25.5 \pm 1.2 \mu\text{g NH}_4^+ \text{ g}^{-1} \text{ h}^{-1}$ ), and catalase activity increased by 28–40% (control:  $22.0 \pm 1.1 \mu\text{mol H}_2\text{O}_2 \text{ g}^{-1} \text{ h}^{-1}$ ; OPB:  $30.5 \pm 1.4 \mu\text{mol H}_2\text{O}_2 \text{ g}^{-1} \text{ h}^{-1}$ ). The most pronounced enhancements were observed in sandy loam soils, likely due to improved aeration and biochar porosity facilitating microbial colonization and enzymatic turnover.

These results suggest that OPB fosters microbial-mediated nutrient cycling and biochemical resilience, contributing to the alleviation of microplastic-induced soil stress.

**Table 4.** Effects of Orange Peel Biochar (OPB) on Microbial Biomass and Soil Enzymatic Activities under Microplastic Stress

| Soil Parameter  | Control (0% OPB) | OPB-Amended Soil (1.0%) | % Change Compared to Control |
|---|------------------|-------------------------|------------------------------|
| Microbial Biomass Carbon (MBC) (mg kg <sup>-1</sup> )                             | 176 ± 9          | 256 ± 12                | ↑ 45%                        |
| Microbial Biomass Nitrogen (MBN) (mg kg <sup>-1</sup> )                           | 26 ± 1.2         | 34 ± 1.5                | ↑ 32%                        |
| Urease Activity ( $\mu\text{g NH}_4^+ \text{ g}^{-1} \text{ h}^{-1}$ )            | 18.5 ± 0.9       | 25.5 ± 1.2              | ↑ 25–38%                     |
| Catalase Activity ( $\mu\text{mol H}_2\text{O}_2 \text{ g}^{-1} \text{ h}^{-1}$ ) | 22.0 ± 1.1       | 30.5 ± 1.4              | ↑ 28–40%                     |

*Effect of orange peel biochar (OPB) amendment on microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), and key soil enzymatic activities under microplastic-stressed conditions. Values represent mean  $\pm$  standard deviation ( $n = 3$ ). OPB application significantly enhanced microbial biomass and nutrient-cycling enzymes, with the most pronounced improvements observed in sandy loam soils, indicating improved microbial colonization, oxidative stress mitigation, and biochemical resilience of soil systems.*

### 3.4. Interactive Effects of OPB Dose and Soil Type

Two-way ANOVA followed by Tukey’s HSD ( $\alpha = 0.05$ ) revealed significant main and interaction effects of OPB dose and soil type on wheat growth, yield, and soil fertility indicators (Table 4). Sandy loam soils were the most responsive to OPB, followed by loamy and clay loam soils. A clear dose–response relationship was observed, with 1.0% OPB producing optimal improvements across all parameters. Higher doses ( $\geq 2.0\%$ ) showed neutral or diminishing effects, particularly in clay loam soils, possibly due to excessive pH buffering or nutrient dilution.

Significant soil  $\times$  OPB interactions ( $p < 0.05$ ) for yield, MBC, and enzyme activities indicate that OPB efficacy is contingent on inherent soil texture and fertility, highlighting the need for site-specific application strategies.

**Table 5.** Interactive effects of orange peel biochar (OPB) dose and soil type on wheat growth, yield, and soil biological properties under microplastic stress

| Soil Type  | OPB Dose (%)  | Grain Yield (g pot <sup>-1</sup> ) | Plant Height (cm)            | Microbial Biomass C (mg kg <sup>-1</sup> ) | Dehydrogenase Activity ( $\mu\text{g TPF g}^{-1} \text{h}^{-1}$ ) |
|------------|---------------|------------------------------------|------------------------------|--|---|
| Sandy loam | 0.0 (Control) | 18.6 $\pm$ 1.2 <sup>d</sup>        | 62.4 $\pm$ 2.1 <sup>c</sup>  | 210 $\pm$ 9 <sup>e</sup>                   | 18.3 $\pm$ 1.0 <sup>e</sup>                                       |
|            | 0.5           | 22.9 $\pm$ 1.4 <sup>c</sup>        | 68.5 $\pm$ 2.4 <sup>b</sup>  | 265 $\pm$ 11 <sup>c</sup>                  | 24.6 $\pm$ 1.3 <sup>c</sup>                                       |
|            | 1.0           | 27.8 $\pm$ 1.6 <sup>a</sup>        | 75.2 $\pm$ 2.7 <sup>a</sup>  | 325 $\pm$ 14 <sup>a</sup>                  | 31.8 $\pm$ 1.5 <sup>a</sup>                                       |
|            | 2.0           | 26.1 $\pm$ 1.5 <sup>b</sup>        | 72.6 $\pm$ 2.5 <sup>ab</sup> | 310 $\pm$ 13 <sup>b</sup>                  | 29.4 $\pm$ 1.4 <sup>b</sup>                                       |
| Loamy      | 0.0           | 17.2 $\pm$ 1.1 <sup>d</sup>        | 60.3 $\pm$ 2.0 <sup>c</sup>  | 195 $\pm$ 8 <sup>e</sup>                   | 16.9 $\pm$ 0.9 <sup>e</sup>                                       |

|           |     |                          |                          |                        |                         |
|-----------|-----|--------------------------|--------------------------|------------------------|-------------------------|
|           | 0.5 | 21.0 ± 1.3 <sup>c</sup>  | 65.8 ± 2.2 <sup>b</sup>  | 245 ± 10 <sup>cd</sup> | 22.1 ± 1.2 <sup>d</sup> |
|           | 1.0 | 24.6 ± 1.4 <sup>ab</sup> | 71.4 ± 2.5 <sup>a</sup>  | 290 ± 12 <sup>b</sup>  | 27.6 ± 1.3 <sup>b</sup> |
|           | 2.0 | 23.2 ± 1.3 <sup>b</sup>  | 69.2 ± 2.3 <sup>ab</sup> | 275 ± 11 <sup>c</sup>  | 25.3 ± 1.2 <sup>c</sup> |
| Clay loam | 0.0 | 16.5 ± 1.0 <sup>d</sup>  | 58.9 ± 1.9 <sup>c</sup>  | 185 ± 7 <sup>e</sup>   | 15.8 ± 0.8 <sup>e</sup> |
|           | 0.5 | 19.6 ± 1.2 <sup>cd</sup> | 63.4 ± 2.1 <sup>b</sup>  | 225 ± 9 <sup>d</sup>   | 19.7 ± 1.0 <sup>d</sup> |
|           | 1.0 | 22.1 ± 1.3 <sup>c</sup>  | 67.9 ± 2.3 <sup>b</sup>  | 260 ± 11 <sup>c</sup>  | 23.8 ± 1.2 <sup>c</sup> |
|           | 2.0 | 20.4 ± 1.2 <sup>cd</sup> | 65.1 ± 2.2 <sup>b</sup>  | 245 ± 10 <sup>cd</sup> | 21.6 ± 1.1 <sup>d</sup> |

*Interactive effects of orange peel biochar (OPB) dose and soil type on wheat yield, growth attributes, and soil biological properties under microplastic stress. Values are mean ± SD (n = 3). Different superscript letters within a column indicate significant differences according to Tukey's HSD test at p < 0.05. Two-way ANOVA showed significant main effects of soil type and OPB dose, as well as significant soil × OPB interaction effects for grain yield, microbial biomass carbon, and enzyme activity.*

### 3.5. Correlation between Soil Fertility, Microbial Activity, and Wheat Yield

Pearson correlation analysis demonstrated strong positive associations between wheat yield and soil biochemical properties (Fig. 3). Yield correlated strongly with SOC ( $r = 0.87$ ,  $p < 0.01$ ), available phosphorus ( $r = 0.81$ ), potassium ( $r = 0.79$ ), and MBC ( $r = 0.85$ ). These correlations support a mechanistic link whereby OPB-mediated improvements in carbon content, nutrient bioavailability, and microbial functionality collectively drive enhanced wheat productivity under microplastic-contaminated conditions.

### 3.6. Conclusion

Moderate application of orange peel biochar (OPB; 1.0% w/w) effectively alleviated microplastic-induced soil degradation and significantly enhanced wheat performance across soil textures, with the strongest responses observed in sandy loam soil. Compared to microplastic-contaminated controls, OPB increased wheat germination (12–28%), biomass accumulation (18–40%), and grain yield (15–32%), while simultaneously improving soil

fertility indicators, including organic carbon (22–45%) and available phosphorus and potassium (18–55%). Biochar amendment also stimulated soil biological functioning, as evidenced by increases in microbial biomass carbon and nitrogen (20–50%) and key enzyme activities such as urease and catalase (18–48%). These improvements were mechanistically linked to reduced oxidative stress, with OPB decreasing reactive oxygen species accumulation by 20–50% and restoring antioxidant enzyme activities (15–40%), thereby enhancing plant stress tolerance and productivity. Higher OPB application rates ( $\geq 2.0\%$ ) did not provide additional benefits, underscoring the importance of dosage optimization. Overall, this study demonstrates that agro-waste-derived orange peel biochar represents a sustainable and effective strategy for mitigating microplastic toxicity and restoring soil–plant system functionality in wheat-based agroecosystems.

#### 4. Discussion

The results of this study show that a moderate (1.0 %) application of orange peel biochar (OPB) significantly improved wheat performance under microplastic stress, enhancing germination, growth, biomass, yield, soil fertility, microbial biomass, and enzyme activities. These outcomes align with existing literature on biochar's benefits in stressed soils, while also highlighting the importance of dose optimization and soil texture. One clear effect was the upward shift in soil pH from acidic baseline levels ( $\approx 5.8$ – $6.0$ ) toward near neutral ( $\sim 6.4$ ) at 1.0 % OPB, along with notable increases in available phosphorus and potassium ( $\sim 25$ – $40$  %). This is consistent with the recognized liming potential of biochar, which results from alkaline ash fractions, oxides, and functional groups that neutralize acidity (Lehmann & Joseph, 2015; “Soil acidification and the liming potential of biochar,” 2022). Indeed, a global meta-analysis found that biochar increases soil pH by an average of 5.59 %, particularly in acidic soils (Zhang et al., 2025) (“The potential of biochar to mitigate soil acidification,” 2025).

By mitigating acidity, biochar improves nutrient retention (especially P, K, and base cations), reduces leaching, and enhances cation exchange capacity, thereby enhancing fertility (Ippolito et al., 2012; “Biochar Production and Characteristics, Its Impacts on Soil Health,” 2024). These chemical changes provide a stronger substrate for root growth, nutrient uptake, and microbial activity, consistent with your observed yield correlations ( $r$  between yield and OC, P, K, MBC).our finding of  $\sim 20$  % increase in soil organic carbon (SOC) under OPB suggests that biochar contributed stable carbon and improved soil physical structure. Many studies report that biochar's porous nature and recalcitrant carbon contribute to carbon

sequestration, increase water retention and improve soil aggregation (Lehmann & Joseph, 2015; “Biochar Production and Characteristics, Its Impacts on Soil Health,” 2024). Enhanced SOC often provides better habitat for microbes, promoting microbial growth and nutritional cycling. The strong correlation between SOC and yield ( $r = 0.87$ ) in your data supports the idea of a feedback loop: improved soil carbon enhances microbial activity and nutrient cycling, which further supports plant growth. A central outcome of your experiment was the substantial increase in microbial biomass carbon (MBC ~45 % increase) and nitrogen (MBN ~32 %), along with elevated urease and catalase enzyme activities. These biological responses are key, as microbial biomass and enzymes drive nutrient transformation, organic matter decomposition, and soil health. Meta-analyses of biochar effects on soil microbial communities confirm that microbial biomass generally increases with biochar amendment, although responses vary depending on biochar properties, soil type, and experimental context (Luo et al., 2024; “Effects of biochar on soil microbial communities: A meta-analysis,” 2023). The positive enzymatic responses you observed align with those in microplastic-stress mitigation studies: Su et al. (2024) reported that biochar addition alleviated the suppressive effect of polyethylene microplastics on enzyme activity and microbial biomass (Su et al., 2024). Enhanced urease suggests greater rates of nitrogen mineralization, supporting plant nitrogen needs; higher catalase suggests improved capacity to detoxify reactive oxygen species, contributing to microbial resilience under stress.

One key merit of your study is demonstrating that biochar application can partially reverse harmful effects of microplastic contamination. Microplastics in soils can impair root growth, block pores, disturb water flow, and exert chemical stress on microbes (Elbasiouny et al., 2023). Biochar’s high surface area and adsorption capacity may immobilize microplastic particles, reduce leachate mobility of plastic additives, and isolate microplastic from roots and microbes. In fact, studies applying biochar in microplastic contaminated soils (Su et al., 2024) reported improved plant performance, nutrient dynamics, and enzyme activities, consistent with your findings. Moreover, the interactive effect of biochar and microplastics was explored in a study where straw biochar combined with polyethylene microplastics affected microbial biomass and greenhouse gas emissions (Li et al., 2022). They showed that biochar can modulate microbial responses under microplastic presence (Li et al., 2022). Thus, your results add empirical weight to the concept that biochar is useful in restoring soil function in microplastic-stressed systems. Your observation that 1.0 % OPB yielded best results, whereas higher rates (2.0 %) failed to deliver extra gains, is consistent with many

biochar studies that find an optimal amendment window. Extremely high dosages may lead to negative effects such as nitrogen immobilization, reduced soil aeration, or imbalanced fertility (Agegnehu et al., 2017; “Effects of biochar on soil chemical properties: A global meta-analysis,” 2022). Also, differential response across soil types (strongest in sandy loam, less in clay loam) aligns with meta-analytic findings showing that biochar tends to have stronger effects in coarse-textured soils where soil structure, water retention, and porosity are limiting (Xu et al., 2025; “Response of soil pH to biochar application in farmland across China,” 2025). In clay soils, existing structure, CEC, and nutrient retention reduce the marginal benefit of amendment.

our data showing a 15–18 % germination boost under 1.0 % OPB is particularly interesting. While germination is less frequently reported, the improved soil conditions (pH, moisture, nutrient availability, reduced microplastic toxicity) likely facilitated better seed germination under stress. The study by Su et al. (2024) observed that biochar helps ameliorate microbial and nutrient suppression caused by microplastics, which in turn can support earlier plant life stages including germination (Su et al., 2024).

## 5. Limitations and Future Directions

While the findings of this study provide strong evidence for the effectiveness of orange peel biochar (OPB) in mitigating microplastic-induced soil stress, several limitations warrant consideration and point toward future research priorities. First, the performance of biochar is strongly dependent on its physicochemical characteristics, including pyrolysis temperature, surface functional groups, ash content, porosity, and stability. Variability in these properties can significantly influence biochar–soil interactions, nutrient dynamics, pH regulation, and microbial responses (Wang et al., 2024; *The key role of biochar in amending acidic soil*, 2025). Future studies should therefore include comprehensive physicochemical characterization of OPB batches to improve reproducibility and mechanistic interpretation.

Second, the present findings are based on pot-scale or short-term experimental conditions, which may overestimate biochar benefits due to controlled environments and limited soil volume. Long-term field experiments across multiple growing seasons are essential to assess the persistence of OPB effects, potential saturation or aging phenomena, biochar stability, and cumulative impacts on soil health and crop productivity under realistic agronomic conditions.

Third, this study focused on a specific type and size range of polyethylene microplastics, whereas agricultural soils are exposed to a diverse mixture of polymers differing in size,

shape, surface chemistry, and additive composition. Future research should evaluate the interactions between biochar and a broader spectrum of microplastic types to improve the generalizability of biochar-based remediation strategies.

Finally, potential trade-offs and unintended effects associated with higher biochar application rates require careful evaluation. Excessive biochar inputs may lead to nitrogen immobilization, increased soil electrical conductivity, altered soil moisture dynamics, or shifts in greenhouse gas fluxes. In addition, the long-term fate of contaminants sorbed onto biochar and their secondary ecological effects remain insufficiently understood (Cayuela et al., 2017; *Effects of biochar on soil chemical properties: A global meta-analysis*, 2022). Addressing these aspects will be critical for developing balanced, sustainable, and field-applicable biochar management strategies for microplastic-contaminated agroecosystems.

## **6. Implications and Recommendations**

The findings of this study demonstrate that orange peel biochar (OPB), produced from agricultural waste, represents a cost-effective and sustainable amendment for mitigating microplastic-induced soil degradation while simultaneously enhancing crop productivity. The observed positive correlations among wheat yield, soil organic carbon (SOC), microbial biomass, and nutrient availability underscore the integrative benefits of biochar, reflecting its capacity to improve soil structure, nutrient retention, and microbial function in a coordinated manner. By immobilizing microplastic particles, alleviating oxidative stress, and promoting soil enzymatic activity, OPB supports a holistic soil–plant system restoration.

For practical implementation, it is critical to tailor OPB application rates to specific soil conditions, including texture, baseline fertility, and local environmental factors. The present study indicates that a moderate application rate (~1% w/w) optimally balances agronomic and ecological benefits, avoiding potential trade-offs such as nutrient imbalances or altered soil moisture dynamics that may occur at higher biochar levels. To facilitate broader adoption, long-term field-scale trials are recommended to validate laboratory and pot-scale findings, assess biochar persistence, monitor cumulative effects, and enable localized calibration of application rates for diverse agroecosystems. Incorporating OPB into circular agricultural practices not only provides an effective strategy for rehabilitating microplastic-impacted soils but also contributes to sustainable waste valorization and resilient crop production systems.

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