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Enhancing the Antioxidant Enzyme Activities and Soil Microbial Biomass of tomato plants against the stress of Sodium Dodecyl Sulfate by the application of bamboo biochar

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Abstract

Sodium dodecyl sulfate (SDS) is also known as sodium lauryl sulfate; it is an organic compound and anionic surfactant used in most sectors. SOD is a detergent that is used primarily extensively in soap manufacturing industry. It is also used in personal care products in concentrations of 0.1-1%, and in laboratory applications, its concentrations increased up to 2-10%. However, the widespread use of SDS has raised environmental concerns and has become a hazard to soil microbial communities, crucial to soil health and fertility. To decrease these effects, a bamboo biochar application was used for a pot experiment. Bamboo is a rapidly growing plant that can supply a steady stream of feedstock for biochar production. Applying bamboo biochar increased the Soil microbial biomass carbon (MBC) and nitrogen (MBN), chlorophyll content, and antioxidant enzymatic activity. It has a high porosity level and, therefore, stores essential nutrients like nitrogen, phosphorus, and potassium in soil (NPK), which can reduce the bioavailability of SDS. At the same, this application also reduced the oxidative stress of reactive oxygen species. The result of the present study offers a sustainable solution for decreasing the effects of SDS on tomato plants and assessing the role of bamboo biochar in mitigating stress due to SDS induction.

Keywords: SDS-induced stress; Tomato, Microbial Biomass, biochar, antioxidants.

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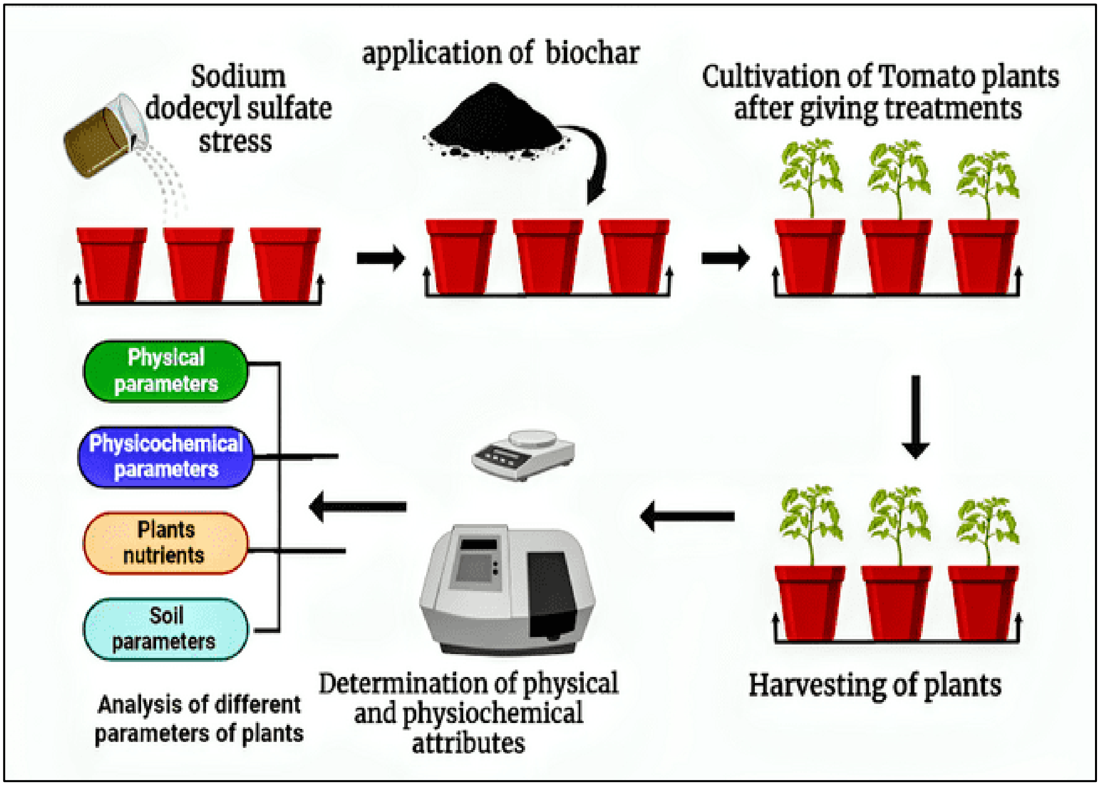

Graphical abstract

Introduction

Sodium dodecyl sulfate, a commonly used anionic surfactant, has applications spanning industries, with concentrations as high as 0.1-1% in personal care products and 2-10% in laboratory detergents (Foley et al., 2012). However, burgeoning use leads to environmental accumulation, with concentrations in affected waters reported up to 3 mg/L. Such concentrations have been related to adverse effects on plants, especially tomatoes, where exposure to only one mg/L of SDS could provoke a 25% reduction in growth (Shi et al., 2022). Beyond the plant level, several studies have shown that concentrations of SDS higher than two mg/L have critical implications for adverse changes in the soil's microbial ecosystems, weakening the soil's health (Lewis et al., 2019). Bamboo biochar, therefore, is emerging as a viable solution to such problems, showing capacities of adsorbing SDS of upwards of 100

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mg/g (Li et al., 2024). This confirms its efficiency and sustainability, considering that bamboo is a fast-growing plant and, therefore, it can be harvested at significant rates of approximately 20 tons/ha/year. In addition, bamboo biochar is cost-effective, where the production cost ranges from $50-100/ton. It presents many environmental benefits, such as carbon sequestration and soil conditioning, indicating biochar's ability to bea sustainable solution to SDS contamination (Qu et al., 2022).

The rising environmental accumulation of SDS is a significant source of conflict. According to research, impacted waters, particularly those near industrial settings or densely populated areas, have SDS concentrations of up to 3 mg/L (Verma et al., 2021)vv. The SDS concentration in such type of water is not affected. One of the previously interesting studies examined the effect of SDS on tomato plant development and growth (Ding et al., 2018). The findings were alarming, demonstrating that a single dose of 1 mg/L SDS could cause a 25% reduction in the growth of this critical agricultural crop. Available literature has admirably delved into the effects of SDS on plants. Empirical evidence holds that even at a minimum of 1 mg/L, SDS can lead to a 25% growth inhibition in some species (Visca, 2023;Rehman et al., 2023). Some of the studies conducted in unison showed the remediation powers of biochar, especially bamboo biochar, which exhibited adsorption of more than 100 mg/g capacity for contaminants such as SDS. Along with this study, the specific interaction between SDS and tomatoes is yet to be researched, and it is a crop of worldwide importance (Sant'Ana & Lefsrud, 2018).

The environmental effects of SDS are not limited to the plant kingdom. The delicate balance of soil microbial communities, essential for sustaining soil health and productivity, is also threatened (Kumar et al., 2021; Raza et al., 2023). Existing literature suggests that more than two mg/L concentrations can harm these ecosystems. Such changes can negatively impact soil fertility, disrupt the nutrient cycle, and risk the health of plants growing in affected soils (Farukh & Noureen, 2021;Gavrilescu, 2021). Biochar is a black, carbon-rich, and porous solid material (similar to charcoal) made from the partial burning of biomass wastes such as bones, compost solids, or other plant-derived organic residues in an oxygen-free or oxygen-limited environment, which can improve crop growth and yield (Guo et al., 2016). It can remediate toxins while also acting as a low-carbon emission solution. It is an emerging technique for sustainable alternatives. In a stressful soil environment, biochar is used as a soil additive. Bamboo biochar's potential benefits extend beyond its ability to absorb SDS (A. Hussain et al., 2021;Bilias et al., 2023).

In this study, growing tomato plants will be subjected to different concentrations of SDS treatments, and the results will document growth patterns, fruit yield, and biochemical response in detail and with precision. The choice of the tomato as the model crop is guided by its worldwide culinary importance and being an exemplary model of representative fruit-bearing plants. The overall aim goes beyond academia; this research aims to benefit sustainable agricultural practices. With the rising problems of contaminants in our soil and water, this may be another step toward the beginning of really looking into bamboo biochar as a full-spectrum remediation agent. This study builds on previous literature on the base knowledge of SDS and the remediation capacity of biochar, given the global importance of tomatoes as an essential crop species with which to further investigate biochar's specific interaction. This study aims to fill this knowledge gap with very well-established and rigorous experimental designs that make inroads into the nuances of this interaction. The possible benefits of using bamboo biochar as a mitigation tool are showing a way toward even more sustainable agricultural practices and, at the end of the line, a more sustainable world.

Material and methods

The research was conducted at the Department of Environmental Science, Government College University Faisalabad, in a Controlled Plant Growth Chamber. The temperature, fluctuating between 16 and 25°C, and the humidity, stabilized at 65%, were within the acceptable limits that the chamber maintained. The photoperiod, a constant of 7 hours, guaranteed that the plants grew under the right light. For this purpose, rhizosphere soil samples were carefully collected from Every Green Nursery in Faisalabad. The samples collected in triplicates had a drilling method, taking a depth of 0-15 cm. From these, clean the collected soil samples extensively to prepare for the experiment. Extraneous materials from the soil, such as plant roots, debris, and even fallen leaves, were removed to make the soil uniform in consistency and homogeneity. The soil sieving was done to get a uniform texture, after which the sieved soil was allowed to dry to be free from moisture. The soil's pH and electrical conductivity (EC) were analyzed to provide precision in our analysis. The pH and electrical conductivity (EC) measurements of the soil were taken before experimenting and then after treatments, using fresh, experimental soil; measurements were obtained using standardized protocols. It was a well-laid-out experiment with seven treatments, each with three replications. This arrangement added up to thirty pots: 1 kg of prepared soil filled each pot. Stress was applied to the soil by sodium dodecyl sulfate, ranging from 50 to 100 ppm. Then, at the same time, into the stressed soils, biochar from bamboo was added to the mixture at 5 and 10 g/kg to test the probable effect. Ten tomato seeds were planted inside the pot for the beginning of the germination stage. The number of seedlings per pot was pruned to seven post-germinations to ensure evenness and avoid crowdedness. The primary goal was, therefore, to measure the effects of sodium dodecyl sulfate stress on growth and development where bamboo biochar for the tomato plant is used.

Analysis of physical parameters

The tomato plants were harvested 60 days after germination. Then, they were washed with distilled water to remove adhesive soil. Afterward, using scissors, the roots and shoots were separated from each other and measured for their length accordingly. Fresh weights of the

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seedlings were taken using an electric balance. The dry weights for the root and shoot of the tomato plant were taken after 24 hours of drying in the oven.

Analysis of physiological parameters

The concentration of physiological parameters was evaluated by employing the technique presented by Armon (1949). Specifically, 1g of fresh tomato leaves was homogenized using 2 mL of 80% acetone with a piston and mortar in an ice tub. The chlorophyll a, b, and carotenoid concentrations were measured by absorption at wavelengths of 663, 645, and 480 nm, respectively, utilizing a UV-Vis spectrophotometer (STA-8200V STALWART USA). The chlorophyll and carotenoid content calculations were based on the formula proposed by Lichtenthaler (1987).

Measurement of oxidative stress attributes

The study evaluated stress induced by sodium dodecyl sulfate through the activity of malondialdehyde (MDA) and hydrogen peroxide (H2O2) content. The method delineated by Heath & Packer (1968) was employed to measure MDA activity; for this activity, about 0.5g of fresh tomato leaves were crushed in 5 ml of 0.1% trichloroacetic acid (TCA). The mixture was then centrifuged with Thiobarbituric acid (as a reagent) in TCA, and the concentration of MDA was determined using a spectrophotometer. Hydrogen peroxide content in the tomato leaves was determined based on the protocol by Jana & Choudhuri (1982), with absorbance measured at 390 nm using the STA-8200V spectrophotometer.

Determination of antioxidant attributes

The concentration of Ascorbate peroxidase (APX) was determined by using the method of Amako et al. (1994), and the enzyme activity was monitored by assessing absorbance alterations at 290 nm with a spectrophotometer (STA-8200V, STALWART USA). Peroxidase activity was determined by following Zhang's (1992) technique, and a spectrophotometer measured absorbance at approximately 470 nm. APX enzymes were prominently present in various cellular compartments. Their concentration was measured based on a methodology by Amako et al. (1994). Catalase activity (CAT) was evaluated using the same method, and absorbance was observed at 240 nm.

Phenolic and plant NPK determination

Tomato plant phenolic concentration was assessed using the method described by (2005). After processing the plant samples, their absorbance was read at 463 nm. The sodium, potassium, and calcium concentration in plant roots and shoot was determined using a flame photometer (Sherwood, Model 360) (Jackson, 1958).

Soil analysis techniques

EC was assessed through the saturation extract method outlined by the US Salinity Laboratory (Richards, 1954). Soil phosphorus levels were determined using the Richards. The soil's available potassium was measured with the flame photometer technique described by the US Salinity Laboratory. The organic matter content and total N (%) in the soil were estimated using methods presented by the Walkley-Black (Estefan et al., 2013) and by Kjeldahl (Bremner, 1960), respectively, at intervals of 20, 60, and 120 days. Soil nitrate evaluations were conducted using the chronotropic acid method described by (Shah et al., 2022). Microbial biomass carbon and nitrogen were analyzed by standard procedures through chloroform fumigation and extraction in K2SO4 (Brookes et al., 1985;Vance et al., 1987).

Statistical analysis

Statistical scrutiny was executed employing a complete randomized design (CRD) using Statistics (8.1) software. Parameters were deduced from the variance analysis (CRD) using one-way ANOVA. The least significant difference test was incorporated, noting significant parameter variances at $P < 0.05$.

Results

Plant physical growth parameters

Lower concentrations of SDS (50 ppm) resulted in a noticeable decline in the shoot fresh weight of tomato plants. The weight was significantly reduced with increased SDS concentrations at (100 ppm) ($p < 0.05$), as shown in (Figure 1). Adding Bamboo Biochar at different levels reduced the adverse effects of SDS, particularly at 50 ppm SDS with ten g/L biochar. However, when high SDS concentrations (100 ppm) were combined with more minor biochar levels (5 g/L), the growth parameters of the Tomato plant were inhibited compared to the control.

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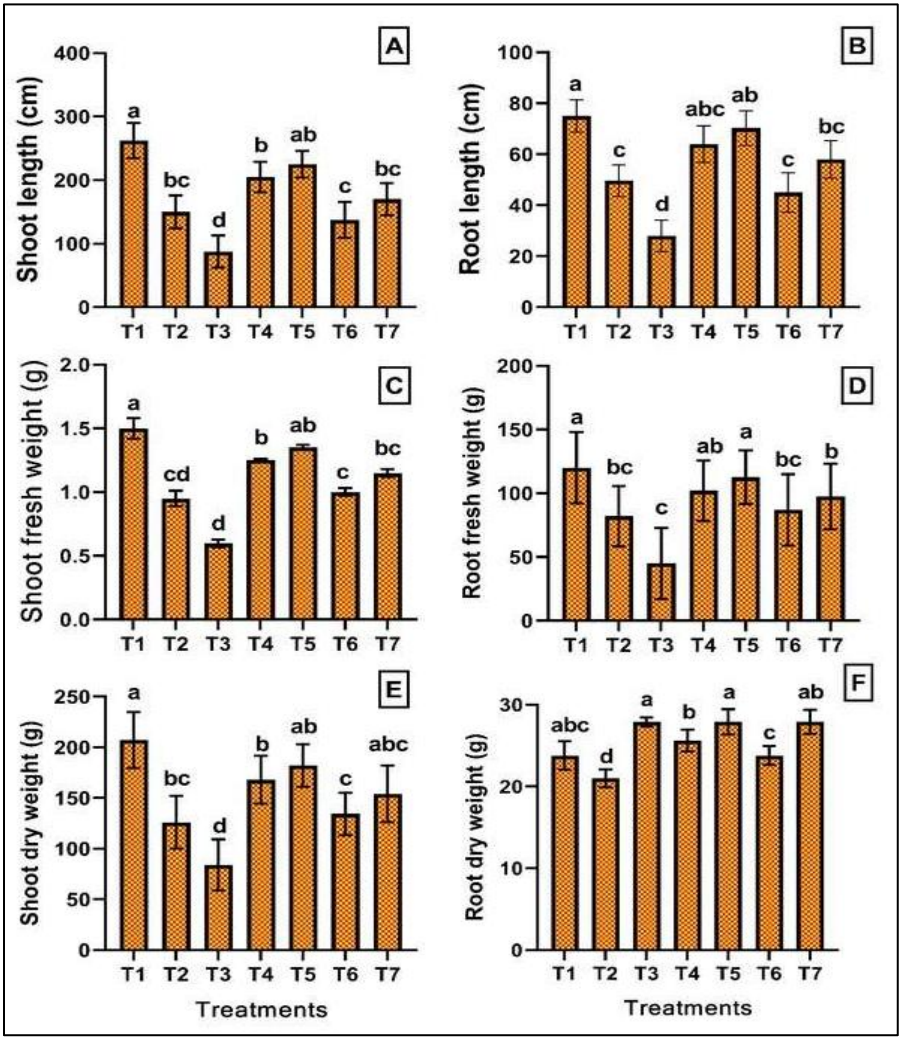

Figure. 1 Effect of biochar application on the shoot length (A), root length (B), shoot fresh weight (C), root fresh weight (D), shoot dry weight (E), and root dry weight (F) of tomato plants under the stress of sodium dodecyl sulfate. Where T1 (control), T2 (50ppm SDA), T3 (100 ppm), T4 (50ppm SDA+ 5mg Biochar), T5(50ppm SDA+ 10mg Biochar), T6 (100ppm SDA+ 5mg Biochar), and T7 (100ppm SDA+ 10mg Biochar. Values are the mean of three

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replicates (n=3 ± SD). Different letters between the treatments show a significant difference among the treatments.

Photosynthetic Pigments

In comparison to the control group (T1), chlorophyll a (Chl A) content decreased significantly ($p < 0.01$) when exposed to increasing the amounts of SDS, particularly at 100 ppm SDS (T3), as shown in (Fig. 2a). Bamboo Biochar appeared to reduce these reductions; for example, combining 50 ppm SDS with ten g/L Biochar (T5) maintained the Chl A and Chl B concentrations more effectively than SDS alone. The protective effect was less apparent when 100 ppm SDS was combined with five g/L Biochar (T6); however, a larger biochar dosage (10 g/L in (T7) modestly improved Chl A and Chl B concentrations (Fig. 2c). The ratio of Chl A/B remained generally stable throughout treatments, indicating a continuous interaction between Chl A and Chl B despite variable SDS.

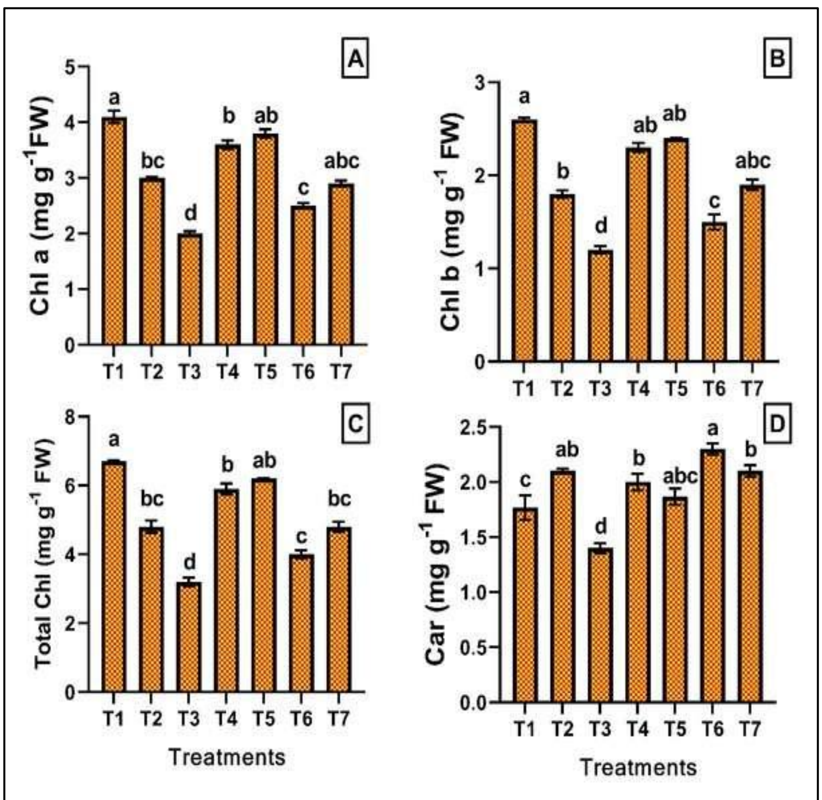

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Figure. 2 Effects of biochar application on the Chlorophyll a (A), Chlorophyll b (B), Total chlorophyll (C), and carotenoids (D) of tomato plants under the stress of sodium dodecyl sulfate. Where T1 (control), T2 (50ppm SDA), T3 (100 ppm), T4 (50ppm SDA+ 5mg Biochar), T5(50ppm SDA+ 10mg Biochar), T6 (100ppm SDA+ 5mg Biochar), and T7 (100ppm SDA+ 10mg Biochar. Values are the mean of three replicates (n=3 ± SD). Different letters between the treatments show a significant difference among the treatments.

Antioxidants

Significant changes in the antioxidant enzyme activities of treated plants were detected in the presence of increased sodium dodecyl sulfate (SDS) concentrations. SOD activity increased significantly under high single exposure levels, notably when SDS reached or exceeded 100 ppm ($p < 0.01$), as shown (figure 3 A-D). Treatments with bamboo biochar, particularly (T4 to T7), showed a moderating increase in SOD activity, bringing it closer to control levels, which indicates bamboo biochar's possible protective role. Concurrently, compared to the control, CAT activity was reduced by nearly 28% and 40% in treatment T2 and T3 with SDS levels of 50 and 100 ppm, respectively. However, applying bamboo biochar across T4 to T7 treatments resulted in a reviving tendency in CAT activities, confirming biochar's anti-SDS-induced stress effect. However, applied bamboo biochar across T4 to T7 treatments resulted in a revived trend in CAT activities, confirming biochar's anti-SDS-induced stress effect.

Impact of SDS on Oxidative Stress and Plant Vitality

Elevated exposure concentrations of SDS manifested notable shifts in various oxidative stress markers and plant growth parameters (Figure 3 E-F). Specifically, high singular exposure concentrations (SDS≥50 ppm) resulted in a discernible increase in MDA concentration, reflective of escalated lipid peroxidation ($p < 0.01$). This trend was most pronounced without bamboo biochar (T3). Similarly, an upward trend in H2O2 levels with increasing SDS was evident, with T3 recording the peak, signifying enhanced oxidative stress ($p < 0.05$). Remarkably, the integration of bamboo biochar (T4 and T5) modulated this oxidative surge more pronouncedly at a ten g/L biochar dosage combined with 50 ppm SDS (T5). However, the oxidative challenge persisted at an elevated SDS concentration of 100 ppm (T6), albeit with a subtle amelioration with higher biochar concentration (T7).

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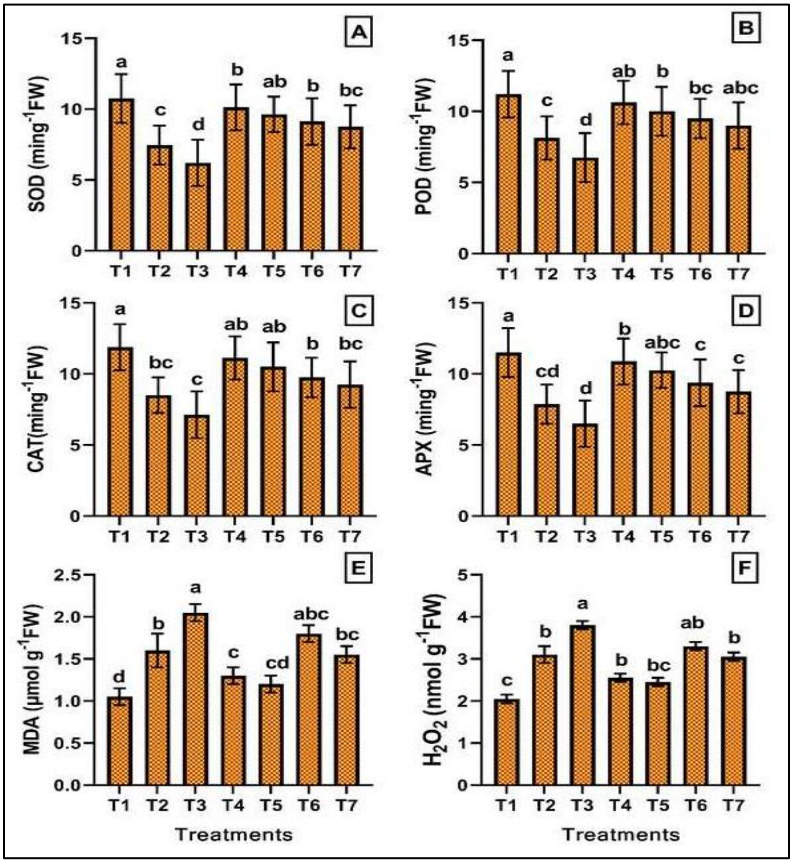

Figure. 3 Effects of biochar application on the superoxide dismutase (A), peroxide dismutase (B), catalase (C), ascorbate peroxidase (D), malondialdehyde (E), and hydrogen peroxide (F) of tomato plants under the stress of sodium dodecyl sulfate. Where T1 (control), T2 (50ppm SDA), T3 (100 ppm), T4 (50ppm SDA+ 5mg Biochar), T5(50ppm SDA+ 10mg Biochar), T6 (100ppm SDA+ 5mg Biochar), and T7 (100ppm SDA+ 10mg Biochar. Values are the mean of three replicates (n=3 ± SD). Different letters between the treatments show a significant difference among the treatments.

Effects of SDS on Tomato Nutrient Uptake and Remediation through Bamboo Biochar

Upon exposure to sodium dodecyl sulfate (SDS), the tomato plants showed an evident variation in nutrient uptake. The T2 treatment (SDS at 50 ppm, without biochar) recorded an 11%

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decrease in Nitrogen, 11.1% decrease in Phosphorus, and 5.5% decrease in Potassium concentrations compared to the T1 positive control (Figure 4). The adverse effects were more pronounced in T3 (100 ppm SDS, without biochar), where reductions of 21.7% in Nitrogen, 19.4% in Phosphorus, and 16.7% in Potassium were observed relative to the T1 positive control. These reductions underscore SDS's inhibitory role in optimal nutrient absorption by tomato plants. The incorporation of bamboo biochar demonstrated its potential as a mitigation strategy. For T4 (50 ppm SDS with five g/L biochar), the values for Nitrogen, Phosphorus, and Potassium saw reductions of 6.5%, 5.6%, and 3.7%, respectively, compared to the positive control. However, increasing the biochar amount in T5 (50 ppm SDS with ten g/L biochar) showcased an uplift with reductions of only 4.3% in Nitrogen, zero change in Phosphorus, and an increment of 1.8% in Potassium compared to T1. At the higher SDS concentration (100 ppm), the remedial influence of biochar was evident but nuanced. In T6 (100 ppm SDS with five g/L biochar), reductions of 17.4% in Nitrogen, 13.9% in Phosphorus, and 11.1% in Potassium were noted relative to T1. However, the T7 treatment (100 ppm SDS with ten g/L biochar) demonstrated an improvement in nutrient uptake, marking reductions of 10.9% in Nitrogen, 8.3% in Phosphorus, and 5.6% in Potassium compared to the positive control.

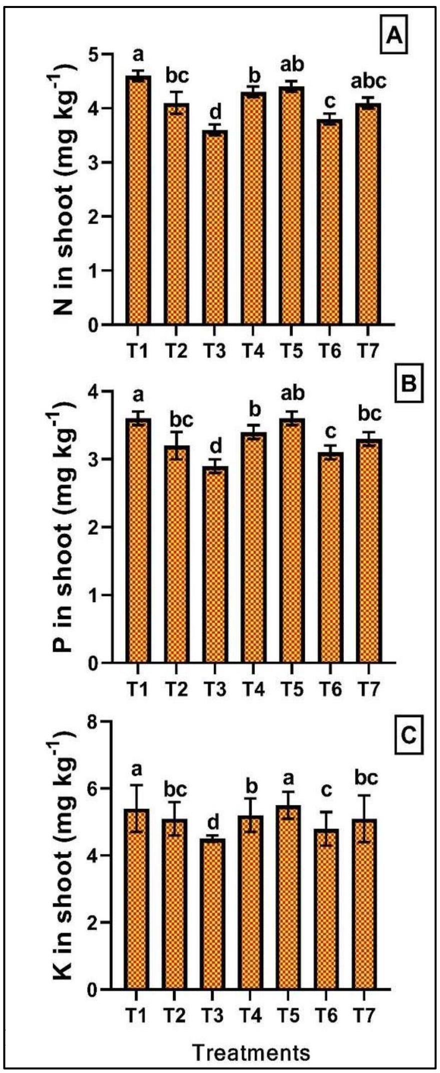

Figure. 4 Effects of biochar application on the nitrogen in the shoot (A), phosphorus in the shoot (B), and potassium in the shoot (C) of tomato plants under the stress of sodium dodecyl sulfate. Where T1 (control), T2 (50ppm SDA), T3 (100 ppm), T4 (50ppm SDA+ 5mg Biochar), T5(50ppm SDA+ 10mg Biochar), T6 (100ppm SDA+ 5mg Biochar), and T7 (100ppm SDA+ 10mg Biochar. Values are the mean of three replicates (n=3 ± SD). Different letters between the treatments show a significant difference among the treatments.

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Response of Soil Parameters to SDS and Bamboo Biochar Application

Electrical conductivity measurements indicated an 184% increase in T2 (Negative Control with 50 ppm SDS) compared to the positive control (T1). This trend was more pronounced for T3 (Negative Control with 100 ppm SDS), showing an increased conductivity of 275% compared to T1 (Figure 5). However, upon introducing biochar in T4 (50 ppm SDS with five g/L biochar) and T5 (50 ppm SDS with ten g/L biochar), there was a decrease in conductivity by 88% and 50%, respectively, as compared to T2. Similar patterns were observed for T6 and T7, suggesting that biochar application mitigated the effects of SDS on soil conductivity.

SDS application without biochar led to an alkalization effect on the soil, with a 5.9% and 10.3% pH increase for T2 and T3, respectively, compared to T1. However, biochar application in treatments T4 through T7 showed a trend of neutralizing the soil's pH closer to the positive control, with T4 and T5 being more effective at lower SDS concentrations. The application of SDS in T2 and T3 decreased organic carbon content by 16.7% and 27.8%, respectively, compared to the positive control (T1). Interestingly, biochar treatments (T4-T7) showed an increase in organic carbon, with T5 having the highest at a 22.2% increase from T1, indicating the potential of biochar in enhancing organic carbon retention. T2 and T3 showed increased ESP by 100% and 200%, respectively, compared to the control. This trend is consistent with SDS being a sodium salt. However, biochar treatments like T4 and T5 exhibited a decrease in ESP by 40% and 30%, respectively, from their SDS-only counterparts (T2 and T3). This suggests that biochar application can reduce the sodium ion accumulation from SDS.

Effects of SDS and Bamboo Biochar on Soil Nutrient Content

Upon examining the soil post-treatment, the Sodium Dodecyl Sulfate (SDS) application and its subsequent remediation through Bamboo Biochar showcased varying impacts on nutrient content (Figure 5). The positive control, T1, with no SDS application, reflected Nitrogen (N), Phosphorus (P), and Potassium (K) content at 180 mg/kg, 25 mg/kg, and 200 mg/kg, respectively. In comparison, the negative controls T2 and T3, with 50 ppm and 100 ppm SDS, displayed reductions in N content by 8.3% and 16.7%, P content by 20% and 28%, and K content by 7.5% and 15%, respectively. However, introducing bamboo biochar posed a considerable remedial effect. Specifically, T4, treated with 50 ppm SDS and five g/L biochar, showcased N, P, and K values almost mirroring the positive control, marking a 2.8% reduction in N, 8% reduction in P, and 2.5% reduction in K. T5, with 50 ppm SDS and a doubled biochar dose of 10 g/L, exhibited an identical N and K content to the control and just a 4% decline in P. In contrast, T6, bearing 100 ppm SDS with five g/L biochar, revealed a decrease of 11.1% in N, 20% in P, and 7.5% in K, identical to T2. However, T7, exposed to 100 ppm SDS but boosted with ten g/L biochar, displayed a rebound with just 5.6% reduction in N, 12% in P, and 2.5% in K. These results underscore the mitigation potential of bamboo biochar against SDS's adverse effects, with biochar quantity playing a pivotal role in nutrient restoration.

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Effects of SDS on Soil Microbial Biomass

Soil microbial biomass carbon (MBC) and nitrogen (MBN) were assessed. The positive control, T1, reflected an MBC of 400 μg/g and MBN of 40 μg/g. Compared to this, the negative controls T2 and T3 with 50 ppm and 100 ppm SDS displayed reductions in MBC by 20.42% and 30% and in MBN by 25% and 37.5%, respectively. However, with the introduction of bamboo biochar, there were improvements. T4 and T5, with 50 ppm SDS and biochar doses of 5 g/L and ten g/L, respectively, saw restorations with MBC reductions narrowing to 6.67% and 2.5% and MBN reductions to 7.5% and 5%. For T6 and T7, with 100 ppm SDS and the same biochar doses, the MBC reductions were 15.42% and 10%, with MBN reductions of 17.5% and 12.5%. This data reinforces bamboo biochar's ameliorative potential in remediating SDS's negative impacts on soil microbial health.

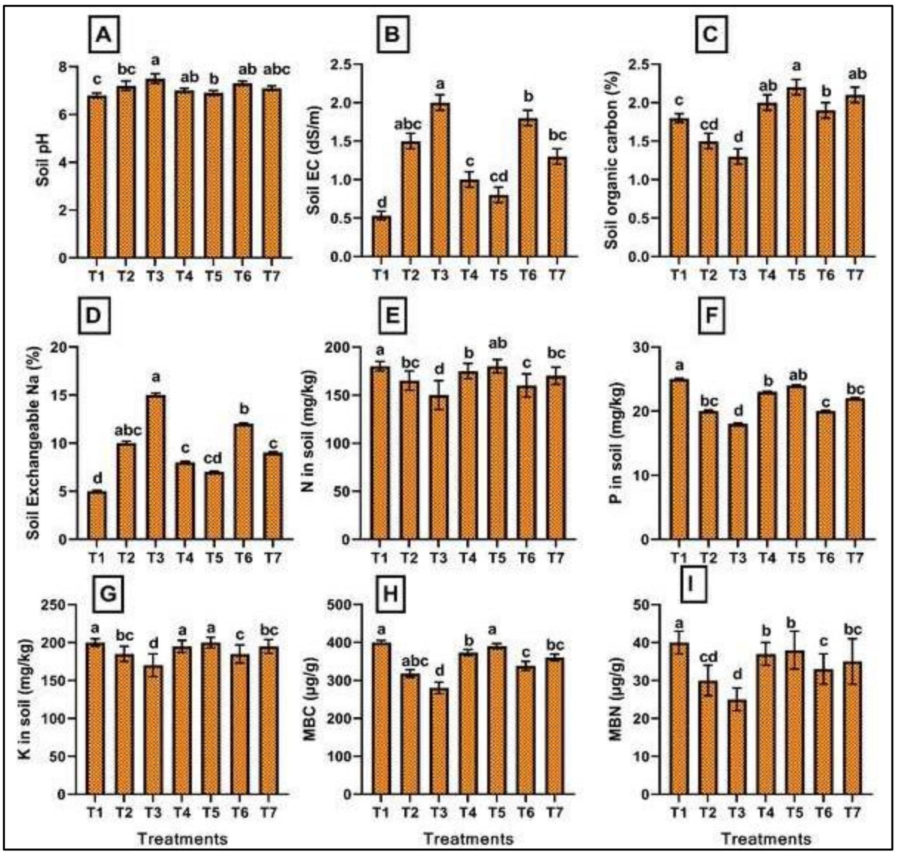

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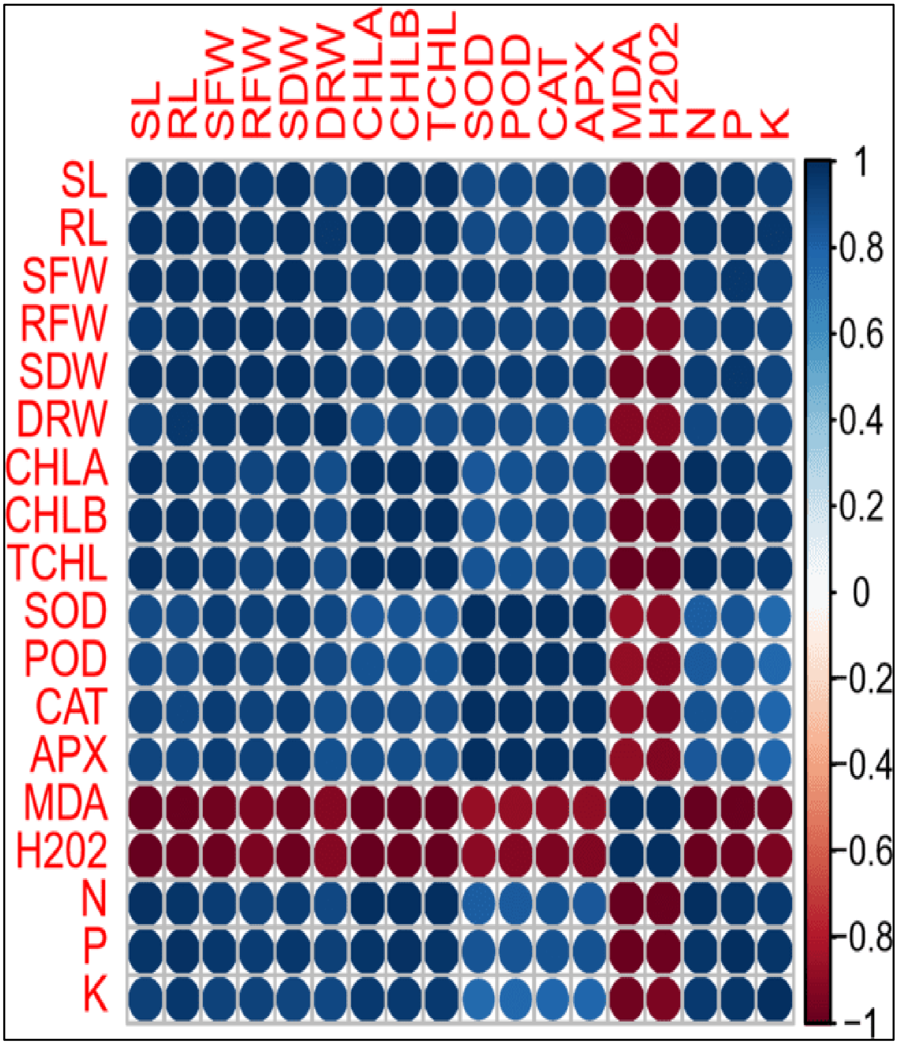
Figure. 5 Effects of biochar application on the soil pH (A), soil EC (B), soil organic carbon (C), soil exchangeable sodium (D), nitrogen in the soil (E), phosphorus in soil (F), potassium in soil (G), soil microbial biomass carbon (H), soil microbial biomass nitrogen (I) after post-harvest of tomato plants under the stress of sodium dodecyl sulfate. Where T1 (control), T2 (50ppm SDA), T3 (100 ppm), T4 (50ppm SDA+ 5mg Biochar), T5(50ppm SDA+ 10mg Biochar), T6 (100ppm SDA+ 5mg Biochar), and T7 (100ppm SDA+ 10mg Biochar. Values are the mean of three replicates (n=3 ± SD). Different letters between the treatments show a significant difference among the treatments.

Correlational analysis

Pearson correlation analysis was conducted between tomato plants' physical and physicochemical parameters (Figure 6). The study of the MDA and H2O2 showed a strong negative correlation with physical growth parameters, photosynthetic pigments, and antioxidant attributes. The principal component analysis (PCA) was conducted between soil attributes under the stress of SDA (Figure 7).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RL
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SDW
DRW
CHLA
CHLB
TCHL
SOD
POD
CAT
APX
MDA
H202
N
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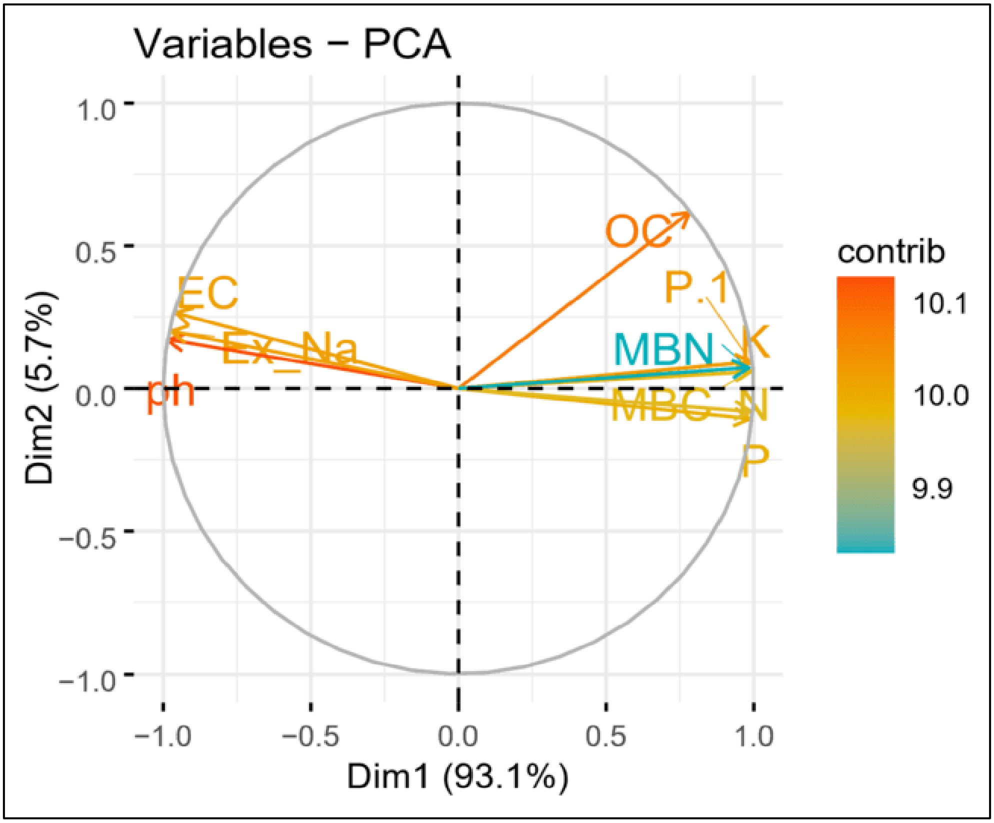
K
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1

Figure 6. Person correlation analysis among the 18 main parameters on studied tomato plants. The red color represents negative correlations, while the blue color demonstrates positive correlations. Abbreviations, RL, root length; SL, shoot length; SFW, shoot fresh weight; RFW, root fresh weight; RDW, root dry weight; SDW, shoot dry weight CHL, chlorophyll content; SOD, superoxide dismutase; POD, peroxidase; CAT, catalase; APX, ascorbate peroxidase;



MDA, malondialdehyde; H2O2, superoxide radical; Photo, photosynthetic rate; N, nitrogen; p, phosphorus; k, potassium concentration in tomato plants.

Figure 7. Principal component analysis (PCA) demonstrates the effects of biochar on different soil attributes after harvesting tomato plants under the stress of sodium dodecyl sulfate.

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Abbreviations: Ex Na, exchangeable sodium; OC, organic carbon; MBN, microbial biomass nitrogen; K, potassium concentration in the soil; MBC, microbial biomass carbon; N, nitrogen concentration in the soil; P, phosphors concentration in soil.

Discussion

The data illustrates a discernible impact of SDS on tomato plant growth metrics, including shoot and root fresh and dry weights and their respective heights. The adverse effects of SDS on plant growth become more pronounced with increasing concentrations. This is evident when comparing T1 (positive control) with the negative controls (T2) and (T3). With 50 ppm of SDS (T2), the plant shoots fresh weight decreased by 36.7%, and the effect intensified to a 60% reduction at 100 ppm SDS (T3) relative to the positive control. Such SDS-induced stress is consistent with the literature, which documents the phytotoxic effects of surfactants on plants, impairing physiological functions and overall growth (Singer, 2012). Remarkably, incorporating bamboo biochar into the soil showed the potential to mitigate these adverse effects. A comparison of T4 and T5, with 50 ppm SDS but varying biochar amounts, revealed that a higher biochar concentration resulted in better plant growth metrics. Specifically, the shoot fresh weight in T5 (1.35 kg) was 8% higher than in T4 (1.25 kg). Similarly, under a higher SDS concentration of 100 ppm, T7 (with more biochar) exhibited better growth parameters than T6. The improvement could be attributed to the sorption capacity of biochar, which likely adsorbs SDS, reducing its bioavailability and toxicity to plants (Wei et al., 2024; Ali et al., 2021; Fdez-Sanromán et al., 2020). The enhanced growth metrics in T4, T5, T6, and T7 compared to their respective controls without biochar (T2 and T3) further emphasized this protective role of biochar. Furthermore, biochar's ability to promote microbial biomass might also play a part in counteracting SDS-induced stress. Soil microorganisms are crucial in nutrient cycling and plant health (Elhenawy et al., 2022; Mekwichai et al., 2024). While this data does not directly provide microbial biomass counts, prior research indicates that increased soil microbial biomass due to biochar addition can improve plant health and stress resistance (Elad et al., 2011; Kolton et al., 2017; Fallah et al., 2023). The results indicate a clear association between the concentration of SDS and a decline in chlorophyll content in tomato plants. Chlorophylls (Chl A and Chl B) and carotenoid content are essential indicators of photosynthetic capacity and plant health (Chou et al., 2020).

The reduction in the chlorophyll content in the presence of SDS, particularly in the cases of T2 and T3, might be corroborated with work carried out by some other scientists that proved surfactants like SDS can interfere with the structure of chloroplasts, which has a direct impact on the photosynthetic process (Shoukat et al., 2023; Wang et al., 2018). The better result in higher biochar concentration is probably because the introduction of bamboo biochar alleviates the effects. The results manifestly illustrate the oxidative stress induced by SDS in tomato plants, primarily characterized by increased malondialdehyde and hydrogen peroxide levels. Both MDA and H2O2 serve as common biomarkers for oxidative damage in plants. The elevation of MDA, a byproduct of lipid peroxidation, from 2 µmol/g in T1 to 3 µmol/g and fourµmol/g in T2 and T3, respectively, indicates enhanced membrane lipid damage under SDS stress.

Similarly, heightened H2O2 levels, a potent reactive oxygen species, affirm the augmentation of oxidative stress with increasing SDS concentrations, echoing previous findings of surfactants triggering ROS production (Motta Mejia, 2018; Dhere & Ghavri, 2023). However, introducing bamboo biochar demonstrates a potential attenuation of this oxidative burden. T4 and T5 treatments show significantly lower MDA and H2O2 values than their SDS-only counterpart, T2 (Gong et al., 2021). Similarly, T6 and T7, despite facing higher SDS stress, still present reduced oxidative markers compared to T3. This highlights biochar's remedial role. Biochar could be sequestering SDS, thus reducing its bioavailability and stress on plants or directly improving soil properties to bolster plant defense mechanisms (Ain et al., 2024;Malik et al., 2022).

The results highlight the detrimental effects of SDS on nutrient assimilation in tomato plants. A gradient decrease in essential nutrients - nitrogen (N), phosphorus (P), and potassium (K) - can be observed as the concentration of SDS increases from T1 to T3. Such a phenomenon may be attributable to the inhibitory action of SDS on nutrient uptake systems, aligning with past studies indicating surfactants' potential to impede root nutrient absorption (Gao et al., 2023; Peréz et al., 2019). However, bamboo biochar applications seem to confer a protective influence. Compared to the respective SDS-only treatments (T2 and T3), both T4-T5 and T6-T7 depict higher N, P, and K contents, suggesting a beneficial role of biochar in ameliorating SDS-induced nutrient stress.

Interestingly, there was an improvement in enzyme activities found in plants treated with bamboo biochar, especially in T4 and T5, which, when compared with T2, showed the most improvement, and similarly in T6 and T7,which were compared with T3. This reflects the possibility that SDS from SDS can be neutralized by bamboo biochar and thus reduce oxidative stress (Haidri et al., 2023; Hussain et al., 2024; Ullah et al., 2024). The benefits of applying biochar are observed in the improvement of soils for plants, thereby creating an efficient environment for plant antioxidant response (Fatima et al., 2024;Ummer et al., 2023;Haidri et al., 2024). Furthermore, Biochar might parallel the adsorption of SDS, and the resultant oxidative repercussions on plants will be minimized (Waseem et al., 2023). The data portray the damage to tomato plants caused by SDS, which is demonstrated by the rise in malondialdehyde and hydrogen peroxide, which signifies oxidative stress.

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With an outstanding porosity and surface area, biochar can serve as a good nutrient repository, enabling their holding and persistent availability for plants. Furthermore, biochar's adsorption properties can decrease the bioavailability of SDS and hence can lead to the mitigation of its adverse effect on nutrient absorption (Li et al., 2023). This study evaluated how land properties change with the addition of SDS and examined the remediation ability of bamboo biochar. The SDS-mediated rise in soil pH was evident after the SDS addition to the soil. The measured pH was 6.85 in the SDS-free aqueous solution, and it rose to 7.2 and 7.5 in the case of 50 ppm and 100 ppm SDS concentration, respectively. In addition, the soil and solution electrical conductivity y of the micelle solution also got higher, which displayed higher salinity. The SDS usage allowed us to reveal a descent in OC content, which could indicate either the processes of organic matter decomposition or microbial metabolism (Behnke et al., 2023). An increase in EPS (Exchangeable Sodium Percentage) indicates that this may lead to instability of the soil structure. The addition of bamboo biochar ameliorated sodium dodecyl sulfate (DS), pH value, and electrical conductivity, thereby reducing salt. This means that biochar is also used to neutralize salination that results from SDS. SDS and improving soil organic carbon contentarecritical factors in nutrient turnover, particularly with more biochar applied (Xu et al., 2021).

The SDS effectivity in the cultivation of tomatoes was assessed. The results, obtained by comparing nitrogen, phosphorus, and potassium levels in T1 and T3, show a significant decline. Meanwhile, the P and K values dropped to 18 mg/kg and 170 mg/kg, respectively. This interference is likely to occur during nutrient fixation, assimilation, and soil structure. Nevertheless, adding bamboo biochar in T4 to T7 was observed to present a positive trend in remediation, and in T5, where 10g/L of biochar was applied, it bested even the other treatments. The mechanism would imply better nutrient retention in soils treated with bamboo biochar and higher microbial activity and cation exchange capacity (Hien et al., 2021; Cruz-Méndez et al., 2021). Furthermore, with a much higher SDS value, there was a significant decrease in MBC and MNB levels after tomato cultivation. At the end of the intervention period, the values reached 280.0 μg/g for MBC and 25.0 μg/g for MBN. On the other hand, with the addition of biochar made from bamboo in treatments T4-T7, they did not recover as well as in the former case, with T5 showing considerable recovery at 390.0 μg/g and 38.0 μg/g, respectively. It indicates that bamboo-derived biochar can enhance the resistance and growth of microorganisms to salinity and drought stress compared to other soils.

Conclusion

The study of sodium dodecyl sulfate effects on tomato plants determined the potential for bamboo biochar usage for environmental pollution of SDS. The outcomes have revealed that bamboo biochar is very effective in improving the plant's performance and diminishing the possible consequences of SDS, which leads to healthier soils. Meanwhile, the study results revealed that it is inevitable to incorporate sustainable materials such as bamboo biochar into agricultural techniques whose primary purpose is to compete with environmental contaminants. Bamboo charcoal can save important crops from destruction by harmful chemicals and make ecosystems more stable, thus promoting the development of more sustainable and robust agricultural practices and the ecosystem's health.

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