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Effects of Biochar on the Physicochemical Properties of Saline-Alkali Soil and the Growth and Metabolism of Melons

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Abstract: To mitigate the adverse effects of soil salinization on melon growth, this experiment utilized two melon cultivars (Cucumis melo L. cv. Tokyo Sweet Treasure and Xizhou Honey No. 17) under three biochar treatments (0%, 10%, and 20% of pot soil mass) and three salt solution irrigations (0, 75, 150 mmol/L). Physiological changes in melons and soil physicochemical properties were investigated at 7, 14, and 21 days post-treatment. Results demonstrated that biochar addition alleviated salt stress-induced inhibition of plant growth and soil degradation. Biochar promoted plant height, root elongation, and antioxidant enzyme activities, with maximum increases of 15.7% (SOD), 29.9% (POD), and 37.5% (CAT). Malondialdehyde (MDA) content decreased initially (up to 44.32%) and later increased. Moreover, optimal biochar ratios enhanced photosynthetic efficiency and significantly increased soil organic matter, while N, P, and K levels showed slight but upward trends. In conclusion, appropriate biochar application improves saline-alkali soil properties, enhances melon growth, and strengthens salt tolerance.

1. Introduction

Soil salinization poses a significant challenge to global agricultural production, forestry development, and ecological balance. It inflicts damage on plants through osmotic stress, ion toxicity, and oxidative stress, thereby inhibiting crop growth[1]. Extensive studies have revealed that prolonged salt stress reduces the relative height, basal diameter growth, and biomass of Chionanthus retusus Lindl. seedlings[2], disrupts ion homeostasis in barley (Hordeum vulgare L.)[3], and induces reactive oxygen species (ROS) accumulation[4]. Furthermore, high salt-alkali content in soil reduces organic phosphorus (P) and exchangeable calcium (Ca) levels, while pH and hydrolyzable nitrogen (N) exhibit fluctuating trends[5].

Melon (Cucumis melo L.), an economically valuable annual vine from the Cucurbitaceae family, is extensively cultivated worldwide[6]. However, soil salinization, exacerbated by unsustainable land use practices, has become a critical constraint to the high-yield and sustainable development of the melon industry in China[7]. Consequently, identifying effective strategies to mitigate salt stress is imperative for expanding melon cultivation and enhancing economic returns. Biochar, a porous carbon-rich material produced through pyrolysis of organic waste under oxygen-limited conditions[8], has gained attention as a soil amendment due to its capacity to elevate soil pH, improve cation exchange capacity (CEC), and immobilize organic and inorganic pollutants[9]. Previous studies demonstrate that biochar reduces salt content in wheat (Triticum aestivum L.) fields[10], enhances potato (Solanum tuberosum L.) stem biomass, root length, and tuber yield[11], and ameliorates soil physicochemical properties and plant responses under abiotic stress[12]. Despite these advances, the role of biochar in regulating salt tolerance physiology in melon remains unexplored.

2. Materials and Methods

2.1 Experimental Design

Seeds of two melon cultivars (Cucumis melo L. cv. Tokyo Sweet and Xizhoumi No. 17) were sterilized and soaked in water for 12 hours. After germination, they were planted in trays filled with a sterile growth medium (sand and gravel). Uniform seedlings were selected and transplanted into pots containing soil mixed with different biochar ratios (w/w): 0% (Control, BC0), 10% (BC10), and 20% (BC20). Two seedlings were planted per pot, and after 5 days of acclimatization, salt-alkali stress treatments were initiated. A preliminary trial with salt concentrations ranging from 0 to 250 mmol/L identified 150 mmol/L as the maximum sub-lethal concentration for subsequent experiments. Three salt solutions (composed of Na2CO3 and NaHCO3 at a 1:1 molar ratio) were applied: 0 (S0), 75 (S75), and 150 (S150) mmol/L. The experiment followed a randomized block design with three replicates. Melon physiological parameters were measured at 7, 14, and 21 days post-treatment, and soil properties were analyzed after 21 days.

2.2 Experimental Methods

Plant height and root length were measured using a 3-m steel tape. Chlorophyll content was determined via the acetone grinding method. A PAM-210 chlorophyll fluorescence analyzer was used to quantify chlorophyll fluorescence parameters. Superoxide dismutase (SOD) activity in leaves was assessed using nitroblue tetrazolium (NBT) photoreduction, peroxidase (POD) activity via guaiacol oxidation, and catalase (CAT) activity using ultraviolet absorption. Malondialdehyde (MDA) content was measured with thiobarbituric acid (TBA) reaction. Soil pH was determined using a PHS-2F pH meter. Soil organic matter was analyzed via the potassium dichromate oxidation-colorimetric method. Phosphorus (P) content was measured using sodium bicarbonate extraction-molybdenum-antimony anti-spectrophotometry, potassium (K) via sodium tetraphenylborate gravimetry, and nitrogen (N) via the Kjeldahl method.

2.3 Data Analysis

Experimental data were statistically analyzed using SPSS 21.0 software. One-way ANOVA and Duncan's multiple comparison test ($\alpha = 0.05$) were employed to calculate means and standard errors.Origin 8.5 software was used for graphical visualization, with results expressed as mean ± standard error and analyzed based on variation rates.

3. Results and Analysis

3.1 Effects of Biochar on Plant Height and Root Length Under Salt Stress

After 21 days of treatment with 75 mmol/L and 150 mmol/L salt solutions alone, plant height of Tokyo Sweet decreased by 25.29% and 15.10%, respectively, while that of Xizhoumi No. 17 decreased by 15.86% and 28.50%. Under 10% and 20% biochar treatments without salt stress, plant height of Tokyo Sweet decreased by 45.91% and 21.22%, and that of Xizhoumi No. 17 decreased by 28.57% and 31.92%. However, when biochar and salt stress were applied together, plant height increased in both cultivars. At 20% biochar, the maximum increases in plant height were 155.25% for Tokyo Sweet and 115.63% for Xizhoumi No. 17. Root length decreased under salt stress alone but improved with biochar addition, showing maximum increases of 105.78% in Tokyo Sweet and 60.42% in Xizhoumi No. 17. These results indicate that salt stress inhibits melon growth, while appropriate biochar concentrations alleviate its negative effects.

3.2 Effects of Biochar on Physicochemical Properties of Saline-Alkali Soil

3.2.1 Soil Organic Matter

Under low-salt (75 mmol/L) and high-salt (150 mmol/L) conditions without biochar, soil organic matter decreased by 26.91% and 39.90% for Tokyo Sweet, and 24.64% and 39.54% for Xizhoumi No. 17, respectively. Biochar amendments mitigated these declines. The smallest reductions in organic matter under biochar treatments were 17.70% for Tokyo Sweet and 16.77% for Xizhoumi No. 17, indicating that biochar enhances soil organic matter retention under salt stress.

3.2.2 Soil N, P, and K Content

Soil nitrogen (N) content showed an initial increase followed by a decline with rising biochar levels, while phosphorus (P) and potassium (K) content positively correlated with biochar concentration under the same salt treatment. Maximum reductions in N, P, and K under salt stress alone were 5.66%, 11.97%, and 14.59%, respectively. Biochar application reversed these trends, with maximum increases of 1.68% (N at 75 mmol/L salt with 10% biochar), 14.27% (P at 75 mmol/L salt with 20% biochar), and 12.19% (K at 150 mmol/L salt with 20% biochar). This suggests that biochar’s porous structure enhances nutrient retention in saline soils.

3.3 Effects of Biochar on Melon MDA Content Under Salt Stress

Malondialdehyde (MDA) content increased significantly under salt stress but decreased with biochar application. At 75 mmol/L salt, MDA in Tokyo Sweet decreased by 44.32% and in Xizhoumi No. 17 by 26.67% with biochar treatment. Under 150 mmol/L salt, maximum reductions were 35.61% for Tokyo Sweet (20% biochar) and 20.23% for Xizhoumi No. 17 (10% biochar). This demonstrates that biochar alleviates oxidative damage caused by salt stress.

3.4 Effects of Biochar on Antioxidant Enzyme Activities

Antioxidant enzyme activities (SOD, POD, CAT) decreased under salt stress but increased with biochar. By day 21, SOD activity in Tokyo Sweet decreased by 13.7% under 150 mmol/L salt alone, but increased by 15.7% at 20% biochar. POD activity decreased by 15.1% under high salt alone but increased by 29.9% with 20% biochar. Similarly, CAT activity decreased by 18.4% under salt stress but rose by 37.5% with biochar. Xizhoumi No. 17 exhibited similar trends, with maximum increases of 12.3% (SOD), 13.9% (POD), and 31.3% (CAT). Optimal enzyme activities occurred at 20% biochar for Tokyo Sweet and 10% biochar for Xizhoumi No. 17.

3.5 Effects of Biochar on Photosynthetic Characteristics

3.5.1 Chlorophyll Content

Salt stress reduced chlorophyll content: 75 mmol/L and 150 mmol/L treatments decreased chlorophyll by 22.83% and 29.95% in Tokyo Sweet, and 19.12% and 31.50% in Xizhoumi No. 17, respectively. Biochar restored chlorophyll levels, with maximum increases of 66.41% in Xizhoumi No. 17 under 75 mmol/L salt with 10% biochar.

3.5.2 Fluorescence Parameters

Initial fluorescence (Fo) and non-photochemical quenching (qN) increased under salt stress but decreased with biochar. For example, Fo in Tokyo Sweet rose by 48.01% under 150 mmol/L salt alone but decreased by 40.66% with 20% biochar. Similarly, the Fv/Fm ratio (photochemical efficiency) declined by 27.34% in Tokyo Sweet under salt stress alone but recovered by 17.26% with biochar. These results confirm that biochar improves photosynthetic efficiency under salt stress.

4. Conclusion and Discussion

Biochar, as a porous alkaline material with strong adsorption capacity and low bulk density, plays a critical role in maintaining normal physiological processes in plants under stress. Numerous studies have shown that applying biochar at appropriate ratios can enhance concentrations of soil nutrients such as N, P, K, and Mg, promote tea (Camellia sinensis (L.) Kuntze) growth in acidic soils, and reduce cadmium uptake in Chinese cabbage (Brassica pekinensis (Lour.) Rupr.) grown in Cd-contaminated soils using Pennisetum (Setaria viridis (L.) Beauv.) straw-derived biochar. The present study revealed that both low- and high-concentration saline treatments inhibited melon plant height and root elongation, reduced chlorophyll content, increased initial fluorescence (Fo) and non-photochemical quenching coefficient (qN), and decreased the maximum photochemical efficiency (Fv/Fm). With biochar application, these metrics recovered significantly. The Tokyo Sweet cultivar exhibited optimal alleviation under 20% biochar treatment under 150 mmol/L salt stress, whereas Xizhoumi No. 17 showed peak performance with 10% biochar. This suggests that an appropriate biochar ratio can improve the melon cultivation environment, mitigate damage to chlorophyll and the photosynthetic system in leaves caused by saline-alkali soils, enhance photosynthetic structural stability and reaction center activity, and sustain normal photosynthetic function, thereby ensuring robust plant growth.

Under salt stress, rhizospheric soil organic matter and nutrient content decline markedly. Our results confirmed that biochar application increased soil organic matter, N, P, and K levels in both cultivars compared to the control, with Xizhoumi No. 17 experiencing milder salt-alkali stress effects. At 20% biochar, soil organic matter, P, and K content showed the most significant improvements, while N content peaked at 10% biochar. These findings align with those of Yang et al., indicating that biochar activates soil nutrient retention mechanisms, boosts fertility, and enhances oxygen supply potential in saline-alkali soils, facilitating healthy melon growth.

Adverse environmental conditions trigger a surge in malondialdehyde (MDA) content and alterations in antioxidant enzyme activity. Our data demonstrated that salt stress markedly increased MDA levels, particularly as the experiment progressed. Biochar application reduced MDA content, though excessive biochar concentrations caused slight rebounds. Under 75 mmol/L salt stress, MDA levels in both cultivars reached minima with 10% biochar. For 150 mmol/L salt stress, Tokyo Sweet and Xizhoumi No. 17 exhibited optimal MDA reduction at 20% and 10% biochar, respectively. These results suggest that biochar protects cellular integrity by mitigating lipid peroxidation, thereby improving melon salt tolerance, albeit with an optimal concentration threshold. Additionally, SOD, POD, and CAT activities varied significantly but followed similar trends. The cultivars responded differently to biochar: Tokyo Sweet achieved peak enzyme activity under 150 mmol/L salt stress with 20% biochar, while Xizhoumi No. 17 reached maximum activity under 75 mmol/L salt stress with 10% biochar. Biochar treatment induced significant changes in MDA content and antioxidant enzyme activity compared to salt-only groups, demonstrating that biochar activates physiological mechanisms to reduce oxidative stress in melon cells under salt stress, enhances reactive oxygen species (ROS) scavenging capacity, and improves plant adaptation to saline environments.

In conclusion, saline-alkali stress alters melon physiological parameters with cultivar-specific responses. Soil nutrient availability (N, P, K) decreases under stress, inhibiting plant growth. Supplementing 10–20% biochar elevates soil nutrient content, enhances photosynthetic capacity and antioxidant enzyme activity, and mitigates salt-induced damage. This study validates biochar's potential as a soil amendment to rehabilitate degraded saline soils, improve plant stress tolerance, and stimulate sustainable melon growth. Biochar optimizes soil physicochemical properties, particularly permeability, water retention, and nutrient absorption, thereby increasing crop yields. However, excessive biochar application must be avoided to ensure optimal cultivation outcomes. Building on these findings, selecting salt-tolerant cultivars and applying biochar at appropriate concentrations could expand melon cultivation in saline-alkali regions, generating ecological and economic benefits. This approach offers innovative strategies for green, sustainable agricultural development in challenging environments.

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