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Research Article

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Influence of Biochar Application Rates on Watermelon Growth, Yield, and Soil Nutrient Availability

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Abstract

Biochar has emerged as a promising soil amendment with the potential to increase plant growth and improve nutrient availability. Its application not only increases nutrient retention but also supports rhizosphere activity, further accelerating nutrient cycling in the soil. In this study, rice straw biochar was applied at different doses to evaluate its effects on watermelon growth, yield, and soil quality. Six treatments were used: T1 (RDF), T2 (RDF + 1 t/ha biochar), T3 (RDF + 2 t/ha biochar), T4 (RDF + 3 t/ha biochar), T5 (RDF + 4 t/ha biochar), and T6 (RDF + 5 t/ha biochar). Compared with the non-biochar treatment, the biochar treatment significantly improved vine length, leaf number, branch count, and the chlorophyll index. Moreover, biochar application notably increased fruit diameter (+ 43.1%), fruit length (+ 72.4%), yield per plant (+ 41.6%), total soluble solids (TSS) (+ 37.1%), and water content (+ 2.7%) compared to non-biochar treatment (T1). Biochar improved the availability of both micronutrients and macronutrients in the rhizosphere. These findings highlight the potential of biochar to increase crop productivity while improving soil fertility, although the optimal dose for maximizing benefits remains an area of ongoing study.

Keywords

Biochar, Watermelon, Plant growth, Nutrient availability, Growth

Introduction

Watermelon (*Citrullus lanatus*) is a widely cultivated and consumed fruit crop that is renowned for its refreshing taste and high-water content [1]. It is a valuable source of vitamin A and vitamin C, antioxidants, and essential minerals, contributing significantly to human nutrition [2]. However, the cultivation of watermelon faces numerous challenges, including soil degradation, nutrient depletion, and water scarcity, which can adversely affect plant growth and fruit yield [3]. As the global demand for watermelon continues to rise, there is an urgent need to adopt sustainable agricultural practices that increase productivity while preserving environmental health [4]. One promising approach to improve the fertility of land and crop yield is the application of biochar; despite promising results from previous research, the optimal dosage of biochar for specific crops, including watermelon, remains underexplored. In an oxygen-limited environment, the thermal breakdown of feedstocks such as wood, agricultural residue, chicken manure, and grass generates a solid porous carbon-rich substance known as biochar [5]. Biochar application may lower nutrient leaching, promote the health of

the soil, decrease soil acidity, increase fertilizer utilization efficiency, increase crop production, improve total soil carbon and trap more CO_2 from the atmosphere [6]. By adding organic materials to the soil, biochar application can increase key soil nutrients, soil bulk characteristics, and crop production. This positively influences soil biological processes [7, 8]. Both the chemical and physical characteristics of the biochar formed are highly dependent on the type of feedstock used and the temperature at pyrolysis, which impacts the soil [9]. Biochar often improves the pH of soils because of the limited ability of carbonate salts to be retained in the biochar ash component [10]. Alkaline biochar is commonly utilized for soil improvement. The impact of applying biochar on the earliest germination rate of watermelon seeds [11, 12]. The salts are mostly carbonate compounds, hydroxides, volatile metal oxides, soluble minerals, and silicates derived from soil particles found in the feedstock. These mineral salts add to the alkaline properties of biochar. Biochar improves soil nutrient availability by providing a home for beneficial microbes [13], which serve a vital function in nutrient cycling [14]. The high surface area of biochar also allows for the adsorption of essential nutrients, such as nitrogen (N) and phosphorus (P), preventing their leaching and increasing their availability to plants [15]. Additionally, biochar contributes to the water-holding capacity of soil [3], which is particularly beneficial in regions prone to drought. Biochar can increase soil moisture retention, reducing irrigation frequency [16] and ensuring that watermelons receive adequate hydration during critical growth periods. This increase is attributed to the increased nutrient availability and improved water retention provided by biochar, which directly support fruit development. Moreover, biochar has been shown to positively impact the nutritional content of watermelon, increasing the levels of important vitamins and antioxidants [11]. This improvement not only benefits consumer health but also enhances the market value of the produce. Additionally, the unique properties of biochar contribute to reducing the susceptibility of watermelon to pests and diseases. By fostering a healthier soil ecosystem, biochar supports the growth of beneficial microorganisms that can outcompete harmful pathogens. The accessibility of nutrients near the root system is crucial, which means that cations, such as calcium (Ca), potassium (K) and magnesium (Mg), are essential plant nutrients that must be available near the root for transportation to the shoot [17]. Direct utilization of nutrients in the root or their transport via the xylem to active plant tissues is possible [18]. As a result, adding biochar to soil improves the availability of nutrients and N retention, increasing crop yield [19]. The ideal depth for incorporating biochar to maximize nutrient availability remains uncertain [20]. It is essential to balance biochar with plant nutrients to avoid nutrient imbalances that can lead to the adsorption and unavailability of applied nutrients [21]. The strength of soil is closely tied to the accessibility of nutrients, and plants require many soil nutrients, such as N, P, and K. Therefore, incorporating an adequate amount of biochar into the soil can improve plant growth and yield by increasing the availability of essential nutrients while avoiding nutrient imbalances. This study aims to evaluate biochar application rates effects on watermelon growth and yield and analyze their impact on soil chemical properties.

Materials and Methods

Biochar preparation

The biochar was produced from rice straw before it was properly dried. A stainless-steel tub with a height of 48 cm and a circumference of 142 cm was used for the pyrolysis of rice straw under open fire conditions. This process is an autothermal process in which part of the residue burns, which heats the remaining feedstock to turn it into biochar. An open burn tub was used for pyrolysis. It was filled with rice straw feedstock and then ignited. This whole assembly creates a pyrolysis zone, as the carbonization of the feedstocks takes place beneath the flame in the absence of oxygen. The biomass in the assembly does not emit fumes or smoke because there is insufficient oxygen to allow combustion. Rather, it is converted into gas, oil, and high-carbon charcoal. A heat sensor thermometer was used to record the temperature during the pyrolysis of the rice straw, which ranged from 400 °C to 600 °C. Water was used to quench the feedstocks. The biochar was air-dried and stored in bags until field application. The biochar yield was estimated to be between 45% and 50% of the rice straw feedstock used in the pyrolysis process.

Experimental design

The field experiment was carried out in the kharif season of 2024 at the agriculture research farm of Lovely Professional University Punjab, India. The coordinates for the location are latitude 31°14'30.5"N and longitude 75°41'52.1" E. A total of 6 treatments were executed using a randomized block design (RBD), with three replications. Including treatments: T1 (RDF), T2 (RDF + 1 t/ha biochar), T3 (RDF + 2 t/ha biochar), T4 (RDF + 3 t/ha biochar), T5 (RDF + 4 t/ha biochar) and T6 (RDF + 5 t/ha biochar). The jannat variety of watermelon was used for the present investigation.

Plant attributes

Vine length was measured with a flexible measuring tape measure from the starting level to the tip of three randomly selected plants, and the mean length was calculated. A major vine was picked from those that began close to the ground of the plant and extended farthest from the base. Soil plant analysis development meter (502 plus) was used to analyze the chlorophyll indices of the leaves at 30, 60, and 90 days after sowing (DAS). The fruits were harvested at maturity, and juice was extracted from the section of tissue from the center of the fruit. The juice from all the fruits was stored at -20 °C for further analysis. The pH of the watermelon juice was measured at room temperature via a digital pH meter. The TSS content was determined via a TSS digital refractometer (GI-03S).

Soil analysis

Soils from each plot were sampled to a depth of 15 cm before transplanting and after harvesting watermelon. The various features of the soil are examined. The pH and electrical conductivity (EC) were measured with the Hana HI 9813-6 portable pH/EC meter, and the organic carbon (OC) was calculated using Walkley and Black method [22]. Kjeldahl's technique was used to assess available N [23]. The concentrations of P and sulphur (S) were measured calorimetrically

[24], whereas the available K had already been estimated using flame photometry [25]. Other nutrients, such as Mg, iron (Fe), copper (Cu), manganese (Mn), zinc (Zn), and boron (B) were measured using atomic absorption spectroscopy [26].

Statistical analysis

The data were analyzed via R studio software via analysis of variance at a significance threshold of $p < 0.05$ to identify differences between group means. Origin pro software was used to construct graphical representations of the data, allowing for easier visual examination of the findings.

Results

Plant attributes

The application of different doses of biochar had a significant effect on growth attributes, as shown in figure 1. Compared with that in the control treatment (T1), the maximum vin length in watermelon was recorded at 90 DAS; the maximum percentage increase was revealed in T5 (93.5%), followed by T6 (78%), T4 (53.2%), T3 (33.1%) and T2 (15.3%). The same trend was observed for the number of branches, with the maximum branch percentage increase recorded at T5 (77.8%), followed by T6 (50%), T4 (33.3%), T3 (27.8%), and T2 (16.7%), compared with T1. The chlorophyll index is an important metric that provides a clear understanding of the photosynthesis rate and plant growth, which are significantly affected by biochar application. Compared with T1, T5 (14.5%) followed by T6 (12.3%) > T3 (12.2%) > T4 (6.3%) > T2 (3.8%). The number of leaves per plant provides an estimate of plant health, which is also significantly affected by different biochar doses. Compared with the control (T1), the highest number of leaves was revealed in T5 (142%), followed by T4 (89.4%), T6 (88.6%), T3 (53%) and T2 (22.7%). Biochar amendment significantly affected the number of days to flowering, with the earliest flowering occurring at T5 (36.7 DAT), followed by T6 (37 DAT), T4 (43 DAT), T3 (42 DAT), T2 (44.7 DAT), and T1 (49.7 DAT). The earliest fruit formation was recorded in T5 (51.7 DAT), followed by T6 (55.3 DAT), T4 (58 DAT), T3 (59.7 DAT), T2 (58.7 DAT), and T1 (62.3 DAT). Compared with T1, biochar application significantly affected the number of flowers per plant, with the maximum number of flowers revealed at T5 (18.3), followed by T6 (18), T4 (17.7), T3 (15.7), and T2 (13), and the number of fruits per plant at T5 (12.1), followed by T6 (10), T4 (8), T3 (7.3), and T2 (5.7) (Figure 2).

Incorporating biochar at different doses significantly affected watermelon dimensions, such as fruit diameter and fruit length, as shown in figure 3 ($p > 0.05$). Compared with the T1 treatment, biochar application increased the fruit diameter, with the greatest increase in T5 (43.1%), followed by T6 (36%), T4 (28.2%), T3 (21.9%) and T2 (16.4%). Fruit length increased in T5 (72.4%), followed by T6 (63.1), T4 (46.7), T3 (25%) and T2 (8.3%), compared with that in the T1 treatment. Rind thickness affects the self-life of watermelon, and biochar significantly affects rind thickness. The greatest rind thickness was recorded in T3 (12.2%), followed by T2 (10.8%) and T4 (1%), compared with T1 (the control treatment). Compared

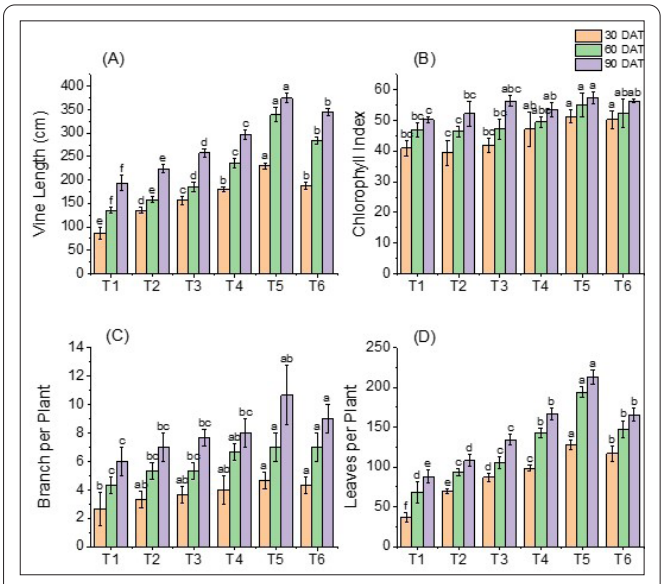


Figure 1: Impact of biochar application on plant **(A)** vine length, **(B)** chlorophyll index, **(C)** number of branches, and **(D)** number of leaves. Different lowercases indicate significant differences between treatments ($p < 0.05$).

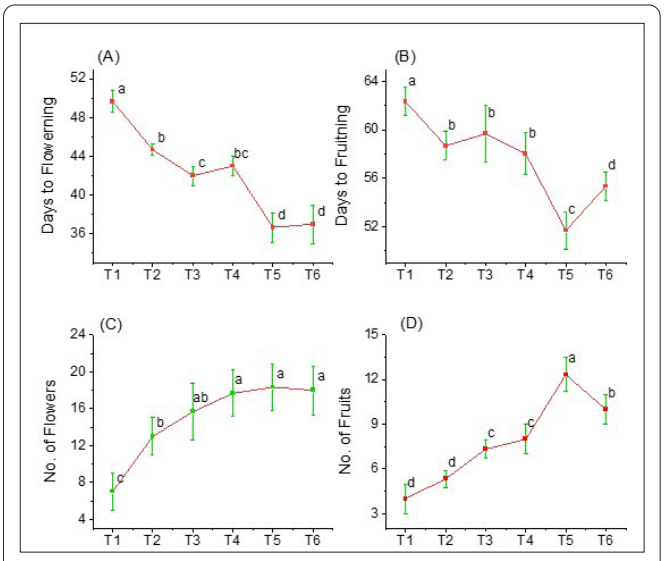


Figure 2: Impact of biochar application on **(A)** days to flowering, **(B)** days to fruiting, **(C)** number of flowers, and **(D)** number of fruits. Different lowercases indicate significant differences between treatments ($p < 0.05$).

with T1, biochar application significantly increased the yield of watermelon per plant in T5 (41.6%), followed by T6 (25.9%), T4 (20.7%), T3 (11.9%), and T2 (3.6%). There was a significant increase in the TSS T5 (37.1%), followed by T4 (24.2%), T6 (22%), T3 (13.6%), and T2 (6.1%), compared with T1. The pH in response to varying doses of biochar was as follows: T5 (6.1) > T6 (5.9) > T4 (5.8) > T2 > (5.7) > T3 = T1 (5.6). Compared with that in the T2 treatment, the water content in the T5 treatment increased significantly (2.7%), followed by T6 (1.7%), T3 (1.6%), T4 (1.1%), and T1 (7%) (Figure 4).

Soil attributes

Soil attributes play crucial roles in crop production, as shown in figure 5 ($p > 0.05$). The soil pH significantly increased as the biochar dose increased, with the maximum pH observed at T6, followed by T5 > T4 > T3 > T2 and T1. Compared with

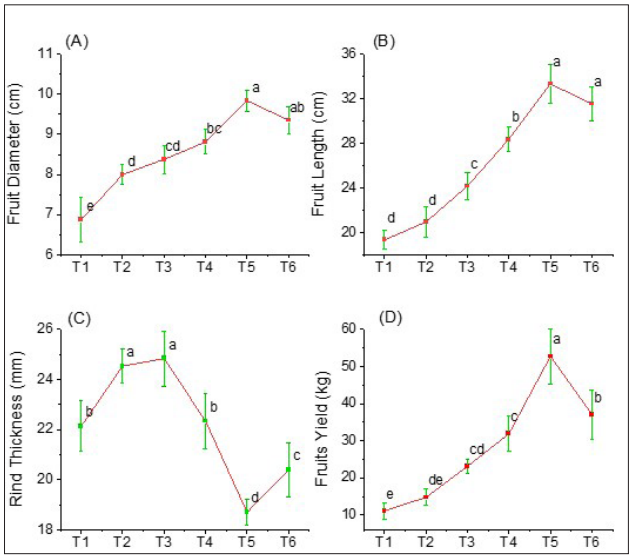


Figure 3: Impact of biochar application on **(A)** fruit diameter, **(B)** fruit length, **(C)** rind thickness, and **(D)** fruit yield per plant. Different lowercases indicate significant differences between treatments ($p < 0.05$).

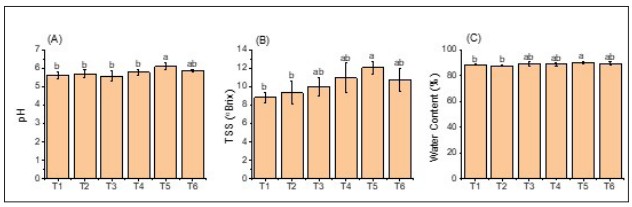


Figure 4: Impact of biochar application on watermelon **(A)** watermelon pH, **(B)** TSS, and **(C)** water content ($p < 0.05$).

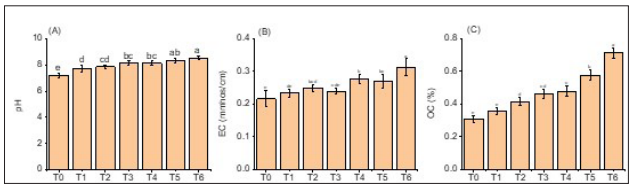


Figure 5: Impact of biochar application on soil soil **(A)** Ph, **(B)** EC, and **(C)** organic carbon. Different lowercases indicate significant differences between treatments ($p < 0.05$).

the T1 treatment, the T6 treatment resulted in a significant increase in EC (34.3%), followed by T4 (18.6%), T5 (15.7%), T2 (7.1%), and T3 (2.9%). The maximum percentage of soil OC increased in T5 (100%), followed by T6 (61.7%), T4 (34.6%), T3 (29.9%), and T2 (16.8%), compared with T1. A significant increase was observed in the N concentration percentage at T6, followed by T5 > T4 > T3 > T2 and T1, with 19.3% > 9% > 3.5% > 2.2% and 0.05%, respectively. Compared with T1, T6 (48.5%) > T5 (30.4%) > T4 (22.4%) > T2 (13.4%) > T3 (7.5%). Biochar is a rich source of K, so the concentration of K significantly increased in the T6 treatment (36.9%), followed by the T5 treatment (21.6%), T4 treatment (13.8%), T3 treatment (12%), and T2 treatment (6.1%) compared with the T1 treatment (Figure 6).

Biochar application altered the soil properties (Figure 7) ($p > 0.05$). Compared with that in the T1 treatment, the concentration of S in the soil significantly increased in the following order: T6 (39.1%) > T3 (24.5%) > T5 (24.2%) > T4

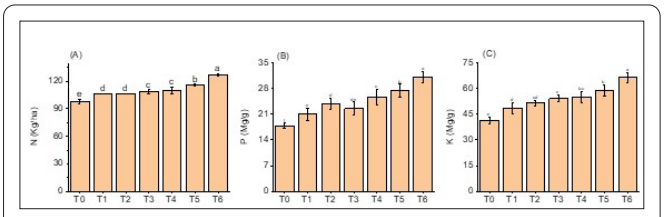


Figure 6: (A) Impact of biochar application on soil N, **(B)** P, and **(C)** K. Different lowercases indicate significant differences between treatments ($p < 0.05$).

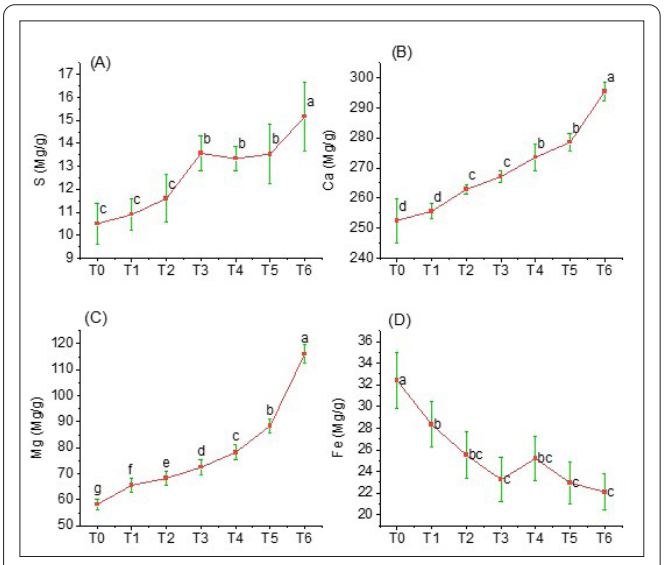


Figure 7: Impact of biochar application on soil **(A)** S, **(B)** Ca, **(C)** Mg, and **(D)** Fe. Different lowercases indicate significant differences between treatments ($p < 0.05$).

(22.3) > T2 (6.4%). Compared with those in the T1 treatment, the Ca and Mg concentrations significantly increased in T6, followed by T5 > T 4 > T3 > T2, 15.6% > 9% > 7% > 4.5% > 2.8 % and 77% > 34.9% > 19.4% > 10.5% > 4.2 %, respectively. The Fe concentration in the soil significantly decreased in the following order: biochar amendments: T1 (28.3) > T2 (25.5) > T4 (25.2) > T3 (23.3) > T5 (23) and T6 (22.1). Compared with T1, biochar application significantly reduced the Cu percentage: T2 (1.4%) < T3 (6.4%) < T4 (10.5%) < T5 (15.5%) < T6 (19.6%). Compared with those in the T2 treatment, the Mn concentration in the soil significantly decreased in the T1 (4.4%) < T3 (11%) < T4 (12.1%) < T5 (21.9%) < T6 (25.3%) treatments. Compared with that in T1, the concentration of Zn in soil significantly increased in T6 (14.6%), followed by T5 (11.2%), T4 (7.9%), T2 (5.6%) and T3 (3.4%). Compared with T1 = T2, the boron concentration significantly increased in T6 (25%), followed by T5 (20.8%), T3 (14.6%) and T4 (12.5%) (Figure 8).

Discussion

Effects on crop attributes

Biochar consists of 70 - 80% carbon and 20 - 30% ash. Ash contains mineral components such as K, Ca, Na, and Mg, and when applied to soil, biochar returns nutrients such as Ca, Mg, K, and P. A meta-analysis indicated that applying biochar improves soil fertility and agricultural yield. This approach is anticipated to address the issue of residue burning and management, which contributes to soil degradation,

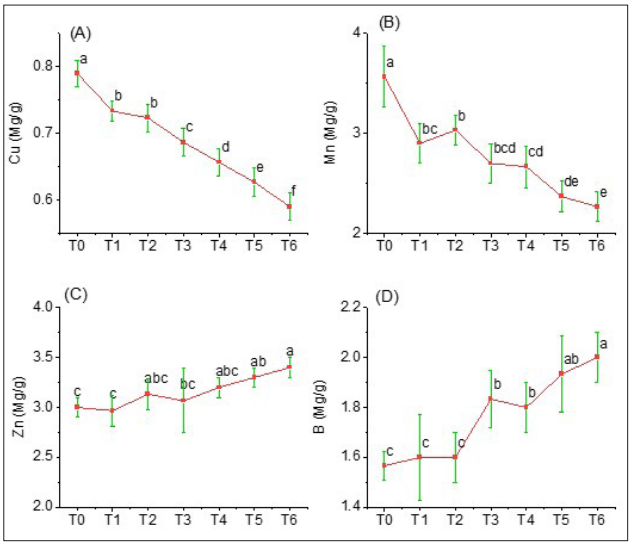


Figure 8: Impact of biochar application on soil **(A)** Cu, **(B)** Mn, **(C)** Zn, and **(D)** B. Different lowercases indicate significant differences between treatments ($p < 0.05$).

GHG emissions, increased heavy metal concentrations, and decreased soil fertility and crop production. Because of its high cation exchange capacity (CEC), biochar has a considerable effect on soil N dynamics [10]. This feature enables biochar to effectively hold and release vital elements, including N, P, and K [27]. K is very important for watermelon growth since it is involved in physiological activities, including photosynthesis, enzyme activity, and osmoregulation [28]. Biochar application can have a considerable influence on flower and fruit formation because of the availability of K [29]. Increasing K levels increase chlorophyll production, which increases the chlorophyll index [28]. A higher chlorophyll index implies better photosynthetic capability, which supports more leaf and total plant development. Biochar increases soil structure and aeration while increasing water retention capacity. The porous structure of biochar improves root respiration and nutrient absorption [30]. This combination of better aeration and moisture retention results in healthier root systems that can absorb nutrients more efficiently. As a result, the vine grows longer, with more branches and leaves, and the increased vegetative growth stimulates blooming and fruiting, eventually contributing to better harvests. Biochar provides a home for beneficial soil microbes and plays an important role in the movement of nutrients and organic matter breakdown [31]. This microbial improvement promotes biomass buildup and enhanced response mechanisms in watermelon plants, ultimately resulting in increased flower and fruit output (Figure 9). The increased leaf area enabled by biochar enables better light interception, which is essential for photosynthesis. This increased photosynthetic activity leads to more vigorous development, as shown by the greater number of fruits and flowers. Furthermore, biochar has been proven to increase plant resistance to environmental challenges, including drought and nutrient deprivation [32]. The ability of biochar to stabilize soil moisture and increase nutrient accessibility helps watermelon plants cope with harsh circumstances, which promotes blooming and fruiting. Biochar treatment improved the physicochemical qualities of watermelon fruits, such as increased water content, TSS, and pH. Higher TSS levels are frequently related to improved fruit sweetness, a desirable characteristic in watermelon. An increase in pH can also improve the overall flavor and nutritional value of the fruit, making it more desirable to customers [33].

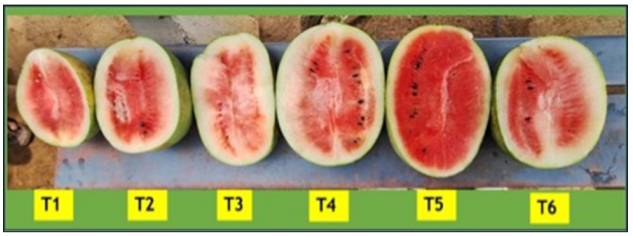


Figure 9: Variations in watermelon color shades and fruit dimensions.

Alterations in soil properties

Biochar amendment improves the soil pH, EC, and OC content via its liming impact, proton consumption processes, high CEC, and capacity to drive microbial activity [34]. This liming action is mostly due to the presence of basic cations, such as Ca and Mg, and carbonates in biochar, which react with soil acids [35]. Furthermore, biochar eliminates soluble ions from the soil, increasing the ionic strength and EC. Furthermore, biochar is high in stable carbon, which contributes to increasing the OC content in the soil. The greatest dosage of biochar increased the OC content in the soil because of its carbon-rich nature, which contributes carbon directly to the soil. The recalcitrant nature of biochar allows it to remain for long periods of time, reducing carbon loss due to breakdown. Biochar also improves soil structure and porosity, allowing for better organic matter retention and encouraging microbial activity, which increases OC generation. Biochar may increase soil carbon and organic matter contents and increase soil microbial activity, which increases soil nutrient availability. Compared with other organic compounds, carbon is more resistant to degradation, facilitating long-term carbon storage and increasing soil fertility [14]. Biochar treatment increases N, P, and K levels in soils. The high CEC and vast surface area of biochar enable it to absorb and store nutrients, limiting leaching and delivering a slow-release fertilizer effect [36]. Additionally, the high pH of biochar enhances P solubility and reduces aluminum toxicity in acidic soils [37]. Ca, Mg, and S. When biochar is added to the soil, it releases these nutrients, increasing their accessibility in the soil. The high CEC of biochar helps it retain and exchange key elements such as Ca, Mg, and S. Biochar helps increase the soil pH, which may increase the mobility and availability of Ca and Mg [34]. Biochar limits the availability of Fe, Cu, and Mn in soil by immobilizing them at relatively high pH values. Biochar can help maintain an ideal balance and avoid any toxicity concerns [38]. The presence of organic functional groups on the biochar surface can promote the formation of stable complexes with metal ions, lowering their mobility and availability. The porous structure of biochar influences the oxidation state of elements such as Fe and Mn [30]. In acidic soils, Zn and boron become less accessible due to precipitation and complexation with other soil components. However, biochar causes the soil to become more alkaline, which increases the Zn and boron concentrations.

Conclusion

In conclusion, the use of biochar at a dose of 4 t/ha has shown considerable benefits in watermelon cultivation. This study revealed that biochar not only increases the soil pH, making important nutrients more readily accessible to plants but also improves fruit shape, allowing better solar collection. As a result of greater photosynthesis, yields increase, and the nutritional conditions of the soil improve. These findings highlight the potential of biochar as an effective soil additive for increasing watermelon output while also contributing to sustainable farming practices. Future studies might investigate the long-term impacts of biochar on the health of the soil and crop performance under various environmental circumstances.

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Conflict of Interest

None.

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References

1. Salin NSM, Saad WMM, Razak HRA, Salim F. 2022. Effect of storage temperatures on physico-chemicals, phytochemicals and antioxidant properties of watermelon juice (*Citrullus lanatus*). *Metabolites* 12(1): 75. https://doi.org/10.3390/metabo12010075
2. Asfaw MD. 2021. Review on watermelon production and nutritional value in Ethiopia. *Food Sci Qual Manag* 104: 11-17.
3. Jabborova D, Annapurna K, Paul S, Kumar S, Saad HA, et al. 2021. Beneficial features of biochar and arbuscular mycorrhiza for improving spinach plant growth, root morphological traits, physiological properties, and soil enzymatic activities. *J Fungi* 7(7): 571. https://doi.org/10.3390/jof7070571
4. Sultana RS, Mahabubur R, Rubaiyat A. 2014. Melon crops improvement through biotechnological techniques for the changing climatic conditions of the 21st century. *Int J Genet Genom* 2(3): 30-41. https://doi.org/10.11648/j.ijgg.20140203.11
5. Kumari K, Kumar R, Bordoloi N, Minkina T, Keswani C, et al. 2023. Unraveling the recent developments in the production technology and efficient applications of biochar for agro-ecosystems. *Agriculture* 13(3): 512. https://doi.org/10.3390/agriculture13030512
6. Alkharabsheh HM, Seleiman MF, Battaglia ML, Shami A, Jalal RS, et al. 2021. Biochar and its broad impacts in soil quality and fertility, nutrient leaching and crop productivity: a review. *Agronomy* 11(5): 993. https://doi.org/10.3390/agronomy11050993
7. Vijayaraghavan K. 2021. The importance of mineral ingredients in biochar production, properties and applications. *Crit Rev Environ Sci Technol* 51(2): 113-139. https://doi.org/10.1080/10643389.2020.1716654
8. Zhang Y, Wang J, Feng Y. 2021. The effects of biochar addition on soil physicochemical properties: a review. *Catena* 202: 105284. https://doi.org/10.1016/j.catena.2021.105284
9. Ippolito JA, Cui L, Kammann C, Wrage-Mönnig N, Estavillo JM, et al. 2020. Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review. *Biochar* 2: 421-438. https://doi.org/10.1007/s42773-020-00067-x
10. Mosharrof M, Uddin MK, Jusop S, Sulaiman MF, Shamsuzzaman SM, et al. 2021. Changes in acidic soil chemical properties and carbon dioxide emission due to biochar and lime treatments. *Agriculture* 11(3): 219. https://doi.org/10.3390/agriculture11030219
11. Juliet OI, Oziri UP, Lawrence ON, Nwachukwu E. 2024. Effect of biochar application on early germination rate of watermelon seeds. *Biochem Mol Biol* 9(1): 7-16. https://doi.org/10.11648/j.bmb.20240901.12
12. Poonia SK, Topno SE, Kerketta A. 2024. Integrated pest and disease management in cucumber and muskmelon. A Monthly Peer Reviewed Magazine for Agriculture and Allied Sciences.
13. Quilliam RS, Glanville HC, Wade SC, Jones DL. 2013. Life in the 'charosphere'–Does biochar in agricultural soil provide a significant habitat for microorganisms? *Soil Biol Biochem* 65: 287-293. https://doi.org/10.1016/j.soilbio.2013.06.004
14. Dai Z, Xiong X, Zhu H, Xu H, Leng P, et al. 2021. Association of biochar properties with changes in soil bacterial, fungal and fauna communities and nutrient cycling processes. *Biochar* 3: 239-254. https://doi.org/10.1007/s42773-021-00099-x
15. Dai Y, Wang W, Lu L, Yan L, Yu D. 2020. Utilization of biochar for the removal of nitrogen and phosphorus. *J Clean Prod* 257: 120573. https://doi.org/10.1016/j.jclepro.2020.120573
16. Haide G, Steffens D, Moser G, Müller C, Kammann CI. 2017. Biochar reduced nitrate leaching and improved soil moisture content without yield improvements in a four-year field study. *Agric Ecosyst Environ* 237: 80-94. https://doi.org/10.1016/j.agee.2016.12.019
17. Skálová H, Jandová K, Balšánková T, Hadincová V, Krahulec F, et al. 2023. Cations make a difference: soil nutrient patches and fine-scale root abundance of individual species in a mountain grassland. *Funct Ecol* 37: 915-928. https://doi.org/10.1111/1365-2435.14277
18. Lynch JP, Strock CF, Schneider HM, Sidhu JS, Ajmera I, et al. 2021. Root anatomy and soil resource capture. *Plant Soil* 466: 21-63. https://doi.org/10.1007/s11104-021-05010-y
19. Diatta AA, Fike JH, Battaglia ML, Galbraith JM, Baig MB. 2020. Effects of biochar on soil fertility and crop productivity in arid regions: a review. *Arab J Geosci* 13: 595. https://doi.org/10.1007/s12517-020-05586-2
20. Fallah N, Yang Z, Tayyab M, Zhang C, Abubakar AY, et al. 2021. Depth-dependent influence of biochar application on the abundance and community structure of diazotrophic under sugarcane growth. *PLoS One* 16: e0253970. https://doi.org/10.1371/journal.pone.0253970
21. Zabaniotou A, Stamou K. 2020. Balancing waste and nutrient flows between urban agglomerations and rural ecosystems: biochar for improving crop growth and urban air quality in the Mediterranean region. *Atmosphere* 11(5): 539. https://doi.org/10.3390/atmos11050539
22. Network GSL. 2019. Standard operating procedure for soil organic carbon: Walkley-Black method, Titration and Colorimetric Method. Food and Agriculture Organization of the United Nations. [https://openknowledge.fao.org/server/api/core/bitstreams/e498d73e-1711-4d18-9183-aa8476387e2c/content] [Accessed May 06, 2025]
23. Sáez-Plaza P, Navas MJ, Wybraniec S, Michałowski T, Asuero AG. 2013. An overview of the Kjeldahl method of nitrogen determination. Part II. Sample preparation, working scale, instrumental finish, and quality control. *Crit Rev Anal Chem* 43(4): 224-272. https://doi.org/10.1080/10408347.2012.751787
24. Food and Agriculture Organization of the United Nations. 2021. Standard Operating Procedure for Soil Available Phosphorus-Olsen Method.
25. Pratt PF. 1965. Potassium. In Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties, pp 1022-1030.

26. Zhang H, Wang Y. 2012. Effects of iron concentration level in extracting solutions from contaminated soils determined by flame atomic absorption spectrometry. *Environ Monit Assess* 184(1): 1-10.
27. Chandra S, Medha I, Bhattacharya J. 2020. Potassium-iron rice straw biochar composite for sorption of nitrate, phosphate, and ammonium ions in soil for timely and controlled release. *Sci Total Environ* 712: 136337. https://doi.org/10.1016/j.scitotenv.2019.136337
28. Ju F, Pang J, Huo Y, Zhu J, Yu K, et al. 2021. Potassium application alleviates the negative effects of salt stress on cotton (*Gossypium hirsutum* L.) yield by improving the ionic homeostasis, photosynthetic capacity and carbohydrate metabolism of the leaf subtending the cotton boll. *Field Crops Res* 272: 108288. https://doi.org/10.1016/j.fcr.2021.108288
29. Sheffield SB, Hoefer TA, Petersen JE. 2024. Biochar has positive but distinct impacts on root, shoot, and fruit production in beans, tomatoes, and willows. *Front Sustain Food Syst* 8: 1346529. https://doi.org/10.3389/fsufs.2024.1346529
30. Liang Y, Tao R, Zhao B, Meng Z, Cheng Y, et al. 2024. Roles of iron and manganese in bimetallic biochar composites for efficient persulfate activation and atrazine removal. *Biochar* 6(1): 41. https://doi.org/10.1007/s42773-024-00331-4
31. Gorovtsov AV, Minkina TM, Mandzhieva SS, Perelomov LV, Soja G, et al. 2020. The mechanisms of biochar interactions with microorganisms in soil. *Environ Geochem Health* 42(8): 2495-2518. https://doi.org/10.1007/s10653-019-00412-5
32. Wu Y, Wang X, Zhang L, Zheng Y, Liu X, et al. 2023. The critical role of biochar to mitigate the adverse impacts of drought and salinity stress in plants. *Front Plant Sci* 14: 1163451. https://doi.org/10.3389/fpls.2023.1163451
33. Almaroai YA, Eissa MA. 2020. Effect of biochar on yield and quality of tomato grown on a metal-contaminated soil. *Sci Hortic* 265: 109210. https://doi.org/10.1016/j.scienta.2020.109210
34. Mendes JDS, Fernandes JD, Chaves LH, Guerra HOC, Tito GA, et al. 2021. Chemical and physical changes of soil amended with biochar. *Water Air Soil Pollut* 232(8): 338. https://doi.org/10.1007/s11270-021-05289-8
35. Gezahegn S, Sain M, Thomas SC. 2019. Variation in feedstock wood chemistry strongly influences biochar liming potential. *Soil Systems* 3(2): 26. https://doi.org/10.3390/soilsystems3020026
36. Hamad AAA, Ni L, Alhaj Hamoud Y, Shaghaleh H. 2024. Incorporation effect of lignin and wheat straw biochar on promoting maize growth and reducing Cd uptake under different irrigation regimes. *Water Air Soil Pollut* 235(7): 462. https://doi.org/10.1007/s11270-024-07269-0
37. Shetty R, Vidya CSN, Prakash NB, lux A, Vaculík M. 2021. Aluminum toxicity in plants and its possible mitigation in acid soils by biochar: a review. *Sci Total Environ* 765: 142744. https://doi.org/10.1016/j.scitotenv.2020.142744
38. Hailegnaw NS, Mercl F, Pračke K, Praus L, Száková J, et al. 2020. The role of biochar and soil properties in determining the available content of Al, Cu, Zn, Mn, and Cd in soil. *Agronomy* 10(6): 885. https://doi.org/10.3390/agronomy10060885