

Effect of Biochar Application on Growth, Yield, and Yield Components of Potato in Logar Province

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ABSTRACT

Optimizing soil management is critical for improving potato (*Solanum tuberosum* L.) productivity in dry temperate regions such as Logar Province. This study was conducted at the Logar Province research farm. It evaluated the effects of eight biochar application rates (0, 5, 10, 15, 20, 25, 30, and 35 t ha⁻¹) on the growth, yield, and tuber quality of the Cardinal potato variety under the agro-climatic conditions of Logar Province, Afghanistan. A field experiment was conducted using a randomized complete block design (RCBD) with three replications. We measured vegetative traits, including plant height and the number of stems, branches, and leaves, alongside key yield components such as tuber number, weight, diameter, and marketable and non-marketable yields. Biochar application significantly increased tuber number, individual tuber weight, and marketable yield, while vegetative traits were largely unaffected, indicating a primary influence on belowground processes. The highest productivity and tuber quality were observed at 20 t ha⁻¹, which also minimized non-marketable tubers. Improvements are attributed to improved soil nutrient retention, water-holding capacity, and microbial activity. These findings provide empirical evidence supporting moderate biochar application at 20 t ha⁻¹ as a sustainable, cost-effective strategy to optimize potato yield, improve tuber quality, and enhance soil health in Logar province semi-arid agroecosystems.

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INTRODUCTION

Potato (*Solanum tuberosum*) is one of the most important food crops internationally, ranking fourth in commodity after rice, wheat, and maize. It is a major source of carbohydrates, vitamins, minerals, and dietary fiber, and plays an important role in ensuring food safety and supporting rural livelihoods. international potato commodity has attained hundreds of millions of tons yearly, reflecting its significance in modern agricultural systems. Nevertheless, climate variability, soil degradation, and inefficient fertilizer use increasingly challenge the potato commodity (Edussuriya et al., 2023a; Xu et al., 2024a).

In Afghanistan, potatoes are a major crop and are widely consumed after wheat and rice. It is widely cultivated in provinces such as Bamyan and Logar, where favorable climatic conditions support tuber production. Among the cultivated varieties, Cardinal is preferred because of its superior yield potential, adaptability, and favorable market properties. Although it is significant, potato fertility in Afghanistan remains relatively low because of poor soil fertility, insufficient nutrient control, irregular rainfall, and drought pressure (Dawerasha et al., 2024).

Soils in semi-arid regions like Logar are characterized by low nutrient accessibility, especially nitrogen and phosphorus shortages, which are critical for plant growth and tuber advancement. Conventional fertilizer practices mostly lead to low nutrient use efficiency, resulting in nutrient losses, environmental pollution, and degrading soil health. Thus, sustainable soil management strategies are needed to enhance nutrient accessibility and improve crop productivity (Dawerasha et al., 2024; Gupta et al., 2023).

Biochar has emerged as a promising soil amendment for improving soil fertility and environmental sustainability. It is a carbon-rich material produced by thermally treating biomass in a limited-oxygen environment. Because of its superior porosity, large surface area, and ability to retain nutrients, biochar can improve soil physical and chemical properties, enhance water retention, and increase nutrient availability. It also improves fertilizer effectiveness by reducing nutrient leaching and serves as a long-term carbon storage material (Gupta et al., 2023; Vilakazi et al., 2023).

Early studies have shown that biochar can improve plant growth, nutrient uptake, and crop yield. In potatoes, biochar has been reported to improve plant length, biomass, and tuber yield, especially when combined with other soil amendments. Additionally, biochar helps develop soil biological activity by providing a favorable environment for beneficial microorganisms. Nevertheless, biochar efficiency depends on factors such as application rate, feedstock type, and soil and climatic conditions (Guo, Zhou, Jia, Wang, Fan, et al., 2025a, 2025b; Hou et al., 2024; Kassaye et al., 2022; Upadhyay et al., 2020).

Although international interest is growing, research on biochar demand in specific agroecological contexts in Afghanistan remains limited. In particular, the response of the Cardinal potato variety to different biochar application rates in the soils of Logar Province remains largely unexplored. This lack of localized research limits the Development of practical, locally relevant recommendations for farmers (Dawerasha et al., 2024; Edussuriya et al., 2023b). thus, this study's goals are:

- To evaluate the effects of different biochar application rates on the growth and yield of potato under the environmental conditions of Logar Province, Afghanistan.

Specifically, the study seeks to determine whether biochar application can improve potato growth and productivity and to identify the application rate that provides the most favorable response under the local growing conditions.

- The study addresses the following research questions:
- How do different biochar application rates affect the growth of potato under the environmental conditions of Logar Province?
- How do different biochar application rates affect potato yield and its components?
- Which biochar application rate results in the most favorable growth and yield of potato under the conditions of Logar Province?

These findings are expected to provide practical recommendations for developing potato production, improving soil fertility, and promoting sustainable agricultural practices in dry temperate areas.

METHODS AND MATERIALS

Study Area

The field experiment was conducted during the 2025 growing season at the Agricultural Research Farm in Logar Province, Afghanistan (34.10° N, 69.0° E; 1,450 m above sea level). The area has a dry, temperate climate with warm summers and frigid winters. During the study period, the mean yearly temperature was about 12.1 °C, ranging from –2.3 °C in winter to 34 °C in summer. Yearly precipitation averaged 332 mm, with peak rainfall happening in April, and the average relative humidity was nearly 50%.

Soil Characteristics

Before planting, we collected soil samples from a depth of 0–30 cm and analyzed them for physicochemical attributes. The soil was classified as sandy loam with a slightly alkaline pH (7.8) and electrical conductivity of 0.259 mS cm⁻¹. Organic matter content was 0.9%, overall nitrogen was 0.03%, and accessible phosphorus was 1.83 ppm. Calcium carbonate was 12%, and cation exchange capacity was 16.4 meq per 100 g of soil, indicating relatively low soil fertility.

Experimental Design and Treatments

The experiment used a randomized complete block design with three replications. The experiment evaluated eight biochar application rates (0, 5, 10, 15, 20, 25, 30, and 35 tons per hectare). Each experimental plot measured 3 m × 3 m (9 m²), with plants spaced 60 cm between rows and 25 cm within rows. We maintained a 0.5 m interval between plots and 1 m between blocks, resulting in 24 plots overall.

Land Preparation and Crop Management

The field was plowed to a depth of 25–30 cm and harrowed to attain a proper seedbed. Biochar was applied at the recommended rates, uniformly distributed, and incorporated into the top 15–20 cm of soil before planting. Suggested doses of nitrogen, phosphorus, and potassium fertilizers were applied uniformly across all treatments, with nitrogen applied in split applications during the vegetative growth stages.

Disease-free seed tubers of the potato variety Cardinal were planted on 25 April 2025 at a depth of 7–10 cm.

Data Collection

Data were collected from ten randomly selected plants per plot. Growth parameters included plant length and the number of leaves, stems, and branches per plant, recorded at 45 and 90 days after planting. Yield parameters were recorded at harvest (approximately 120 days after planting) and included tuber diameter, tuber weight, number of tubers per plant, marketable yield, and non-marketable yield.

Statistical Analysis

All data were analyzed using analysis of variance in the Statistical Tool for Agricultural Research (STAR) software. Treatment means were compared using the least significant difference test at the 5% significance level. The coefficient of variation was calculated to assess experimental variability.

FINDINGS

The study evaluated the impact of varying biochar application rates on potato (*Solanum tuberosum* L.) growth, yield, and quality. Biochar, a carbon-rich product derived from the pyrolysis of organic biomass, is widely recognized for improving soil physical, chemical, and biological properties. Its application can enhance nutrient availability, increase water-holding capacity, and improve soil aeration, all of which collectively influence crop growth and development (Adhikari et al., 2022; Masud et al., 2023; Xie et al., 2022). In this study, we measured key vegetative parameters, including plant height, number of stems, branches, and leaves, alongside yield-related traits such as tuber number, size, weight, and both marketable and non-marketable yield, to assess the effects of biochar and identify the optimal application rate for maximizing productivity.

Biochar significantly affected plant height, a key indicator of early vegetative vigor and overall plant growth, at 45 days after planting (DAP) ($p \leq 0.05$). The tallest plants were recorded in plots receiving 35 t ha⁻¹ (55.53 cm) and 20 t ha⁻¹ biochar (54.40 cm), suggesting that moderate to high biochar application can enhance early shoot elongation, likely due to improved nutrient availability and soil moisture retention. In contrast, treatments with lower biochar rates exhibited reduced plant height, indicating limited improvement in early vegetative growth under suboptimal amendment levels. By 90 DAP, differences in plant height among treatments were statistically non-significant, although the 20 t ha⁻¹ biochar treatment maintained the highest average height (88.73 cm) (Figure 1). This pattern suggests that while biochar strongly influences early-stage growth, its effect on late-season height may be less pronounced, highlighting its role in promoting initial vegetative development rather than final plant stature. These observations align with previous studies showing that biochar primarily improves soil fertility and root development, which indirectly supports shoot growth during early crop stages.

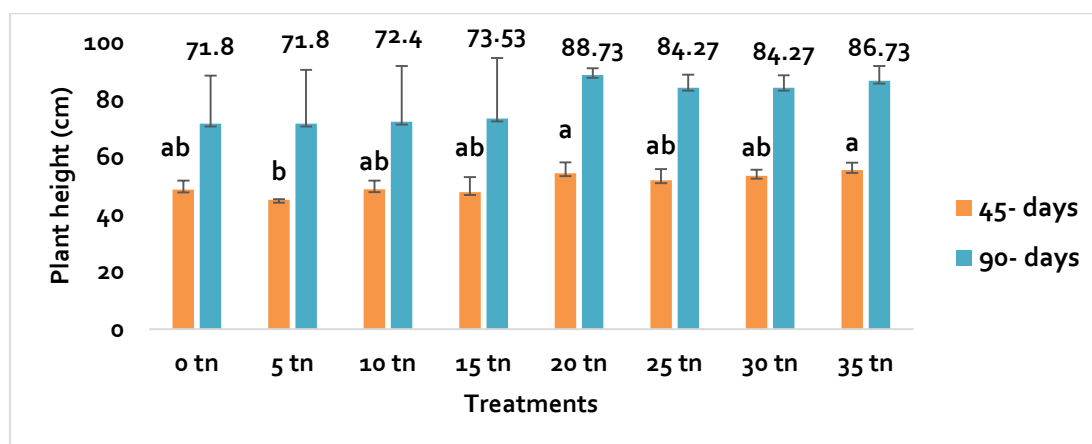


Figure 1. plant height(cm)

Biochar did not significantly affect the number of stems, branches, or leaves per plant at either 45 or 90 days after planting. However, treatments receiving 20–35 t ha⁻¹ generally showed the highest stem and branch counts. This suggests that biochar has limited influence on aboveground vegetative traits, and its primary effects may be directed toward belowground processes such as root growth, nutrient uptake, and tuber development.

In contrast, biochar significantly increased the number of tubers per plant ($p \leq 0.05$). The highest tuber numbers were recorded in treatments receiving 20 t ha⁻¹ (12.43 tubers), 5 t ha⁻¹ (12.10), 30 t ha⁻¹ (12.10), and 35 t ha⁻¹ (11.73), whereas the control treatment produced the lowest number of tubers (9.17). These results indicate that biochar enhances tuber initiation and reduces tuber abortion, likely by improving soil nutrient availability, water retention, and the rhizosphere environment during critical tuber formation stages.

Tuber diameter was highest in the 20 t ha⁻¹ biochar treatment (6.76 cm), although differences among treatments were not statistically significant. The trend, however, suggests that moderate biochar application may promote tuber expansion, possibly through improved soil structure, aeration, and water availability. Similarly, biochar application significantly influenced tuber weight ($p \leq 0.05$), with the greatest weights at 20 t ha⁻¹ (109.68 g) and 35 t ha⁻¹ (109.30 g), indicating that biochar enhances assimilate allocation to underground storage organs and increases individual tuber mass.

Marketable tuber yield was also significantly enhanced by biochar application ($p \leq 0.05$). The highest yield was obtained at 20 t ha⁻¹ (34.41 t ha⁻¹), followed by 35 t ha⁻¹ (28.81 t ha⁻¹) and 30 t ha⁻¹ (28.15 t ha⁻¹), whereas the control treatment produced the lowest marketable yield (17.35 t ha⁻¹) (Figure 2). These results show that moderate biochar application not only improves individual tuber characteristics but also increases overall productivity, highlighting its potential as a sustainable soil amendment to optimize potato yield under the agro-climatic conditions studied.

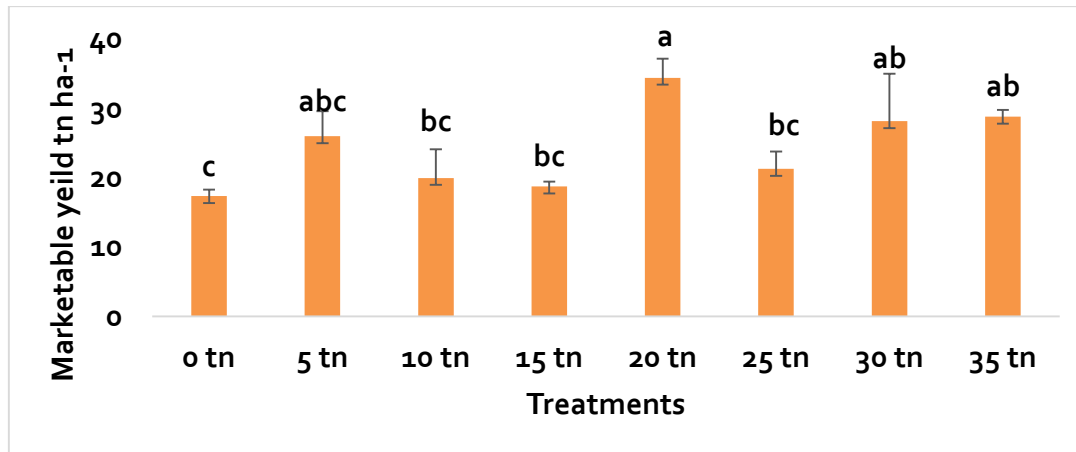


Figure 2. Marketable yield (t per ha)

Biochar application also significantly affected non-marketable tuber yield ($p \leq 0.05$). The highest non-marketable yield was recorded in the 15 t ha⁻¹ treatment (9.39 t ha⁻¹), whereas the lowest values were observed in the 30 t ha⁻¹ (4.87 t ha⁻¹) and 20 t ha⁻¹ (4.97 t ha⁻¹) treatments (Figure 3). This pattern indicates that optimal biochar application not only increases marketable yield but also enhances tuber quality by reducing the proportion of small, malformed, or otherwise unmarketable tubers, likely through improved soil nutrient distribution, moisture retention, and overall growth conditions.

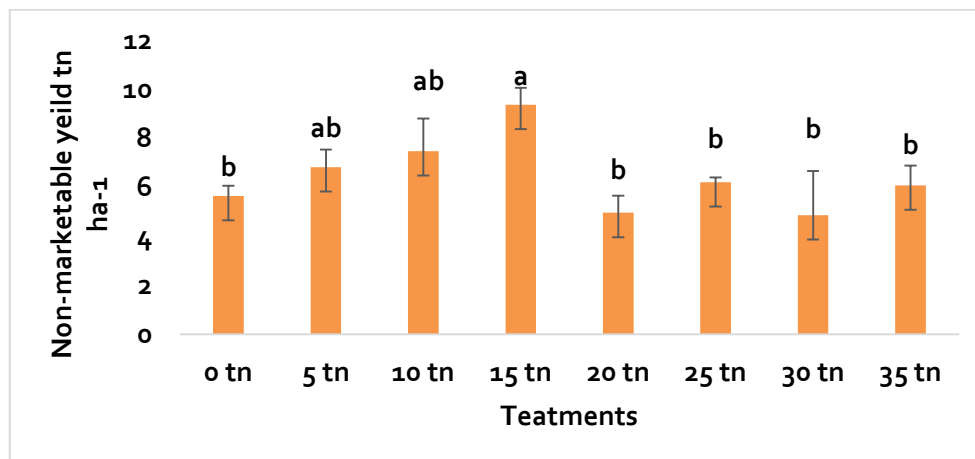


Figure 3. Non-marketable yield (t per ha)

Overall, biochar application, especially at 20 t ha⁻¹, markedly increased tuber number, weight, and marketable yield while reducing non-marketable tubers, highlighting its potential as a sustainable soil amendment for enhancing potato productivity under the experimental conditions. The coefficient of variation (CV) across measured parameters ranged from 4.71% to 22.89%, reflecting acceptable experimental precision and result reliability.

DISCUSSION

The present study evaluated the effects of different biochar application rates on potato (*Solanum tuberosum*) growth, yield, and tuber quality under dry temperate conditions. The results clearly demonstrate that biochar application, particularly at moderate levels, significantly improves yield-related traits, while its effects on vegetative parameters are comparatively limited. These findings directly address the research objective of identifying an optimal biochar rate for enhancing potato productivity (Dawerasha et al., 2024; Guo, Zhou, Jia, Wang, Fan, et al., 2025b, 2025a; Upadhyay et al., 2020).

Tuber diameter showed an increasing trend with biochar application, peaking at 20 ton per hectare, although differences were not statistically significant. This suggests that while biochar may not strongly influence tuber size, it improves soil physical properties such as porosity, aeration, and water retention, which indirectly support tuber expansion. Previous studies reported similar results where biochar improved root development and soil structure without significantly affecting tuber dimensions (Guo, Zhou, Jia, Wang, & Fan, 2025; Guo, Zhou, Jia, Wang, Fan, et al., 2025b; Kassaye et al., 2022a).

In contrast, biochar significantly increased tuber weight and the number of tubers per plant, with the highest values consistently recorded at 20 tons per hectare. These results indicate that biochar plays a crucial role in improving resource use efficiency, particularly through enhanced nutrient retention, increased microbial activity, and improved soil moisture availability. These findings are consistent with earlier studies reporting increased biomass accumulation and yield in biochar-amended soils due to improved rhizosphere conditions and nutrient cycling (Guo, Zhou, Jia, Wang, & Fan, 2025; Hou et al., 2024; Upadhyay et al., 2020).

Marketable yield followed a similar trend, with the highest yield obtained at 20 tons per hectare, confirming that moderate biochar application optimizes both yield quantity and quality. The reduction in non-marketable yield at optimal biochar levels further supports biochar's role in improving tuber uniformity and reducing physiological disorders. These results align with previous research highlighting that biochar enhances soil fertility and reduces abiotic stress, thereby improving crop quality (Dawerasha et al., 2024; Kassaye et al., 2022a, 2022b; Roy et al., 2022).

Plant height was significantly affected during early growth stages but not at later stages, while other vegetative traits such as leaf, branch, and stem number were not significantly influenced. This suggests that biochar primarily affects belowground processes, including root growth, nutrient uptake, and tuber development, rather than aboveground morphology. Similar findings have been reported in other studies, where biochar application showed stronger effects on yield components than on vegetative growth (Liu et al., 2022; H. Wang et al., 2023, 2024; S. Wang et al., 2024; Xu et al., 2024b; Yang et al., 2022, 2024).

Overall, the results indicate that 20 tons per hectare is the optimal biochar application rate under the conditions of this study. Higher application rates did not produce proportional

yield increases, possibly due to nutrient imbalance or diminishing marginal returns at excessive levels. From a practical perspective, moderate biochar application offers a sustainable strategy to improve soil health, enhance nutrient efficiency, and increase potato productivity in dry temperate regions. Furthermore, the use of biochar contributes to climate-smart agriculture through improved carbon sequestration and long-term soil stabilization (Edussuriya et al., 2023a; Guo, Zhou, Jia, Wang, & Fan, 2025; Guo, Zhou, Jia, Wang, Fan, et al., 2025b; Gupta et al., 2023; Xu et al., 2024a, 2024b).

CONCLUSION

This study concluded that biochar application significantly improves potato productivity under dry temperate conditions, with the magnitude of response depending on the application rate. Among the tested treatments, 20 tons per hectare consistently produced the most favorable outcomes by enhancing tuber number, tuber weight, and marketable yield while reducing non-marketable produce. These enhancements can be attributed to improved soil properties, including better nutrient retention, increased water-holding capacity, and improved soil biological activity, which collectively support efficient plant growth and tuber development.

The results provide strong evidence that moderate biochar application is a practical and sustainable soil management strategy for potato cultivation, especially in regions with low soil fertility and water limitations. By improving resource-use efficiency and crop quality, biochar offers a viable alternative to excessive reliance on chemical fertilizers, contributing to more resilient and environmentally sustainable agricultural systems.

Future studies should evaluate biochar performance across multiple growing seasons, soil types, and potato varieties, and explore its integration with other sustainable practices such as organic amendments and microbial inoculants. This research will further refine biochar-based management strategies and support their wider adoption in sustainable agriculture.

Authors contributions

- Ahmad Jawid Zamany conceptualized and supervised the study.
- Nasiruddin Baheej investigated and analyzed data.
- Ajmal Habibi reviewed the manuscript with input from all authors.
- All authors reviewed and approved the final version

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Conflict of interest statement

The authors declare no conflict of interest.

Data availability statement

All data generated or analyzed during this study are available from the corresponding author upon reasonable request. Access to the data is subject to approval to ensure ethical and proper use of the information.

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