International Journal of Agronomy and Agricultural Research
ISSN: 2223-7054 (Print); 2225-3610 (Online) | IJAAR |
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RESEARCH PAPER
Vol. 27, Issue: 5, 2025
OPEN ACCESS

Influence of biochar derived from agricultural waste on soil properties and productivity of carrots (Daucus carota)

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DOI: https://dx.doi.org/10.12692/ijaar/27.5.46-52

ARTICLE INFORMATION

RESEARCH PAPER

Vol. 27, Issue: 5, p. 46-52, 2025

Int. J. Agron. Agri. Res.

Ticman and Ticman

ACCEPTED: 24 November, **2025**

PUBLISHED: 29 November, **2025**

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ABSTRACT

Biochar derived from agricultural waste has attracted considerable attention as a sustainable soil amendment, yet comparative evidence on feedstock-specific effects in root vegetable systems remains limited. This study evaluated the effects of biochar produced from corn cobs, coconut husks, peanut shells, and sugarcane bagasse on soil chemical properties, growth, and productivity of carrot (*Daucus carota* L.) under field conditions. The experiment was conducted from October 2022 to February 2023 using a randomized complete block design with five treatments, including an unamended control, and three replications. Biochar application significantly increased soil pH (from 5.62 in the control to 6.05–6.41), soil organic carbon (from 1.21% to 1.61–1.89%), and available nitrogen (from 48.3 to 61.8–71.6 mg kg^{-1}) relative to the control. Improved soil conditions translated into enhanced carrot growth, with plant height increasing from 42.3 cm in the control to 53.7 cm under corn cob biochar, and root diameter increasing from 3.12 to 4.41 cm. All biochar treatments significantly improved total and marketable yields compared with the control. The highest total yield was obtained with corn cob biochar (23.1 t ha^{-1}), representing an approximately 25% increase over the control (18.4 t ha^{-1}), while marketable yield increased from 15.6 to 20.2 t ha^{-1}. Biochar application also improved root uniformity and visual quality. Overall, the results demonstrate that agricultural-waste-derived biochar, particularly corn cob biochar, enhances soil fertility and carrot productivity and represents a viable, environmentally sustainable alternative to conventional soil fertility management.

Key words: Biochar, Carrot, Soil fertility, Agricultural waste, Sustainable agriculture, Yield improvement

INTRODUCTION

Carrot (*Daucus carota* L.) is one of the most widely cultivated root vegetables worldwide and constitutes an important source of dietary fiber, carotenoids, vitamins, and antioxidants in human diets. Its production contributes substantially to food and nutritional security, as well as income generation for smallholder and peri-urban farmers. However, carrot is highly sensitive to soil conditions, particularly soil fertility, structure, and pH, and its productivity is often constrained in acidic or nutrient-depleted soils that are increasingly common under intensive agricultural systems.

Conventional carrot production systems rely heavily on inorganic fertilizers to satisfy crop nutrient requirements. Although these inputs can enhance yields in the short term, their prolonged and excessive use has been associated with soil acidification, depletion of soil organic matter, nutrient imbalance, and increased risks of nutrient leaching and environmental contamination. Such limitations threaten the long-term sustainability of vegetable-based cropping systems and have intensified interest in alternative soil amendments that improve soil health while maintaining or enhancing crop productivity (Pretty and Bharucha, 2014; Power, 2010).

Biochar, a stable carbon-rich material produced through the pyrolysis of organic biomass under limited oxygen conditions, has emerged as a promising soil amendment in sustainable agriculture. Numerous studies have demonstrated that biochar can improve soil chemical and physical properties by increasing soil pH, enhancing cation exchange capacity, improving water-holding capacity, and promoting nutrient retention (Novak *et al.*, 2014; Wei *et al.*, 2015). In addition to agronomic benefits, biochar contributes to long-term carbon sequestration, thereby supporting climate-smart agricultural strategies and reducing greenhouse gas emissions associated with conventional soil management practices.

The agronomic effectiveness of biochar, however, is strongly influenced by the characteristics of the feedstock and the conditions under which biochar is produced. Biochars derived from different agricultural residues can vary widely in pH, nutrient content, surface area, and functional groups, leading to variable effects on soil fertility and crop performance. Recent research emphasizes that biochar–soil–crop interactions are highly context-specific, necessitating crop- and site-specific evaluation of biochar sources to maximize agronomic benefits (Novak *et al.*, 2014; Wei *et al.*, 2015).

Large quantities of agricultural residues such as corn cobs, coconut husks, peanut shells, and sugarcane bagasse are generated annually and are often underutilized or disposed of through environmentally unsustainable practices. Converting these residues into biochar offers a dual advantage of waste valorization and soil fertility improvement. Previous studies have reported positive effects of biochar on vegetable crops, including improved growth, yield, and nutrient-use efficiency; however, most investigations have focused on single feedstocks or controlled environments. Comparative field-based evaluations of biochar derived from different agricultural wastes, particularly for root crops such as carrot, remain limited.

Recent advances in biochar research highlight the importance of aligning biochar feedstock properties with crop requirements and soil constraints to achieve consistent yield responses. Root vegetables such as carrot may respond particularly strongly to biochar-mediated improvements in soil structure, pH, and nutrient availability due to their direct reliance on favorable root-zone conditions. Despite this potential, empirical evidence comparing the effectiveness of multiple agricultural-waste-derived biochars under field conditions remains insufficient.

Therefore, the present study was undertaken to evaluate the effects of biochar produced from selected agricultural wastes on soil chemical properties, growth, and productivity of carrot under field conditions. Specifically, the objectives were to (i) assess changes in soil pH, organic carbon, and available nitrogen following biochar application, (ii) determine the response of carrot growth and yield to different biochar sources, and (iii) identify the most effective agricultural-waste-derived biochar for improving carrot productivity. The findings are expected to contribute to sustainable soil management strategies and promote the use of locally available agricultural residues as value-added inputs in vegetable production systems.

MATERIALS AND METHODS

Study area and experimental site

The field experiment was conducted at an agricultural research site characterized by acidic soil conditions suitable for carrot cultivation. The site experiences typical tropical climatic conditions, with moderate rainfall and temperature conducive to vegetable production. Prior to experiment establishment, the field was cleared, tilled, and prepared following standard agronomic practices for carrot cultivation.

Biochar preparation and characterization

Biochar used in this study was produced from four different agricultural waste materials: corn cobs, coconut husks, peanut shells, and sugarcane bagasse. These feedstocks were air-dried and subjected to pyrolysis under limited oxygen conditions using a traditional biochar kiln. Pyrolysis temperature was maintained within the commonly recommended range for agricultural biochar production to ensure carbon stabilization and nutrient retention.

The resulting biochars were cooled, ground, and sieved to obtain a uniform particle size prior to soil application. Biochar properties such as alkalinity and carbon content were considered consistent with values commonly reported for agricultural-waste-derived biochars (Novak *et al.*, 2014).

Experimental design and treatments

The experiment was laid out in a **randomized complete block design (RCBD)** with five treatments and three replications. The treatments consisted of:

T1: Control (no biochar application)
T2: Corn cob biochar
T3: Coconut husk biochar
T4: Peanut shell biochar
T5: Sugarcane bagasse biochar

Biochar was incorporated into the soil prior to planting at a uniform application rate across treatments. Each experimental plot received equal agronomic management throughout the growing period.

Crop establishment and management

Carrot (*Daucus carota* L.) seeds were sown directly into prepared plots following recommended spacing for field-grown carrots. Standard cultural practices, including irrigation, manual weed control, and pest monitoring, were applied uniformly across all treatments to minimize confounding effects. No chemical fertilizers were applied to the control or biochar-treated plots to allow evaluation of biochar effects on soil fertility and crop performance. The crop was grown to maturity and harvested after 90 days, consistent with standard carrot production cycles.

Soil sampling and analysis

Soil samples were collected from each plot before treatment application and after harvest. Samples were air-dried, sieved, and analyzed using standard laboratory procedures. Soil pH was determined using a soil–water suspension, while soil organic carbon and available nitrogen were analyzed following established analytical protocols commonly used in soil science research (Wei *et al.*, 2015).

Measurement of growth and yield parameters

Plant growth parameters, including plant height, number of leaves per plant, and root diameter, were recorded at harvest. Plant height was measured from the soil surface to the tip of the longest leaf. Root diameter was measured at the widest portion of the carrot root using a digital caliper.

Yield parameters included total yield and marketable yield, which were determined by harvesting all plants within each plot, weighing the roots, and converting values to a per-hectare basis. Roots exhibiting deformities or damage were excluded from marketable yield calculations.

Statistical analysis

All collected data were subjected to analysis of variance (ANOVA) appropriate for a randomized complete block design. Treatment means were compared using the least significant difference (LSD) test at the 5% probability level ($p < 0.05$). Statistical analysis was conducted using standard statistical procedures widely applied in agricultural research (Gomez and Gomez, 1984).

RESULTS

Effects of biochar on carrot growth parameters

Biochar application significantly influenced vegetative growth of carrot plants (Table 1). All biochar-amended treatments exhibited superior growth compared with the untreated control. Plant height ranged from 42.3 cm in the control to 53.7 cm in plots amended with corn cob biochar. Among the biochar sources, corn cob biochar (T2) resulted in the tallest plants, followed by coconut husk (T3) and peanut shell biochar (T4), while sugarcane bagasse biochar (T5) produced intermediate values.

A similar trend was observed for leaf number. Plants grown under corn cob biochar recorded the highest number of leaves per plant (14.6), significantly exceeding the control, which produced fewer than 10 leaves per plant. Root diameter responded positively to biochar addition, with the largest roots obtained under corn cob biochar (4.41 cm), representing a marked improvement over the control treatment.

Statistical analysis revealed that differences among treatments were significant ($p<0.05$), indicating a strong influence of biochar type on carrot growth performance.

Table 1. Effect of agricultural-waste-derived biochar on growth parameters of carrot

Treatment	Plant height (cm)	Number of leaves plant⁻¹	Root diameter (cm)
T1	42.3 ± 2.1^c	9.8 ± 0.6^c	3.12 ± 0.18^c
T2	53.7 ± 2.8^a	14.6 ± 0.9^a	4.41 ± 0.22^a
T3	50.2 ± 2.5^b	13.2 ± 0.7^b	4.05 ± 0.19^b
T4	48.9 ± 2.3^b	12.8 ± 0.8^b	3.92 ± 0.21^b
T5	47.5 ± 2.4^{bc}	12.1 ± 0.6^{bc}	3.76 ± 0.20^{bc}

Values are mean ± SD (n = 3). Means followed by different letters within a column differ significantly at $p < 0.05$ (LSD test). Treatments consisted of Control (T1), corn cob biochar (T2), coconut husk biochar (T3), peanut shell biochar (T4), and sugarcane bagasse biochar (T5).

Effects of biochar on carrot yield and marketable production

Total and marketable yields of carrot were significantly enhanced by biochar application (Table 2). The control treatment produced the lowest total yield (18.4 t ha^{-1}), whereas all biochar treatments resulted in higher yields. Corn cob biochar produced the maximum total yield (23.1 t ha^{-1}), corresponding to an increase of approximately 25% over the control.

Marketable yield followed the same pattern, with corn cob biochar recording the highest value (20.2 t ha^{-1}). Coconut husk and peanut shell biochars also significantly improved yield relative to the control, though their effects were slightly lower than those observed for corn cob biochar. Sugarcane bagasse biochar showed moderate yield enhancement but remained statistically comparable to other biochar treatments.

The consistent increase in both total and marketable yield demonstrates the effectiveness of agricultural-waste-derived biochars in improving carrot productivity under field conditions.

Table 2. Effect of biochar application on carrot yield parameters

Treatment	Total yield (t ha^{-1})	Marketable yield (t ha^{-1})
T1	18.4 ± 1.2^c	15.6 ± 1.1^c
T2	23.1 ± 1.5^a	20.2 ± 1.4^a
T3	21.7 ± 1.4^b	18.9 ± 1.3^b
T4	21.0 ± 1.3^b	18.3 ± 1.2^b
T5	20.2 ± 1.2^{bc}	17.5 ± 1.1^{bc}

Values are mean ± SD (n = 3). Means followed by different letters within a column differ significantly at $p < 0.05$ (LSD test). Treatments consisted of Control (T1), corn cob biochar (T2), coconut husk biochar (T3), peanut shell biochar (T4), and sugarcane bagasse biochar (T5).

Changes in soil chemical properties following biochar application

Soil chemical properties were significantly altered by biochar incorporation (Table 3). Soil pH increased in all biochar-treated plots compared with the control, indicating a liming effect of biochar. The highest soil pH was recorded under corn cob biochar (6.41), whereas the control remained acidic (5.62).

Organic carbon content increased substantially following biochar application. Corn cob biochar resulted in the highest soil organic carbon (1.89%), followed by coconut husk and peanut shell biochars. Available nitrogen content also increased significantly under biochar treatments, with values ranging from 61.8 to 71.6 mg kg^{-1} compared with 48.3 mg kg^{-1} in the control.

These improvements in soil properties corresponded closely with observed enhancements in carrot growth and yield.

Table 3. Changes in selected soil properties after biochar application

Treatment	Soil pH	Organic carbon (%)	Available N ($mg\ kg^{-1}$)
T1	5.62 ± 0.08[c]	1.21 ± 0.07[c]	48.3 ± 3.2[c]
T2	6.41 ± 0.10[a]	1.89 ± 0.09[a]	71.6 ± 4.1[a]
T3	6.23 ± 0.09[b]	1.75 ± 0.08[b]	66.4 ± 3.8[b]
T4	6.18 ± 0.08[b]	1.69 ± 0.07[b]	64.9 ± 3.5[b]
T5	6.05 ± 0.07[bc]	1.61 ± 0.06[bc]	61.8 ± 3.4[bc]

DISCUSSION

Biochar-mediated enhancement of carrot growth

The significant improvement in carrot growth parameters observed under biochar-amended treatments can be attributed to the well-documented capacity of biochar to modify soil physical and chemical properties in favor of plant development. Increased plant height, leaf number, and root diameter in biochar-treated plots suggest enhanced nutrient availability and improved root-zone conditions. Biochar is known to increase soil porosity and water-holding capacity, which facilitates root proliferation and nutrient uptake, particularly in sandy or degraded soils (Novak *et al.*, 2014).

Among the biochar sources evaluated, corn cob biochar consistently produced superior growth responses. This may be related to its pyrolysis-derived characteristics, such as higher surface area and greater cation exchange capacity, which enhance nutrient adsorption and gradual release to plants (Novak *et al.*, 2014). Improved vegetative growth is particularly important for carrot, as early canopy development supports photosynthate accumulation required for root enlargement.

Yield improvement and agronomic relevance

The substantial increase in total and marketable carrot yield under biochar application highlights the agronomic potential of agricultural-waste-derived biochars. The approximately 25% yield increase recorded under corn cob biochar compared with the control reflects improved nutrient-use efficiency and favorable soil conditions during the growing period. Similar yield-enhancing effects of biochar have been reported in vegetable cropping systems, where improved soil fertility and nutrient retention reduce yield limitations associated with conventional management practices (Roberts *et al.*, 2015).

Enhanced marketable yield further indicates that biochar not only increased biomass production but also improved root quality and uniformity, which are critical attributes for commercial carrot production. Such improvements are particularly relevant in the context of sustainable intensification, where increasing productivity must be achieved without compromising soil health or environmental quality (Pretty and Bharucha, 2014).

Soil chemical improvement as a driver of productivity

Biochar-induced changes in soil chemical properties played a central role in driving improved carrot performance. The increase in soil pH following biochar application suggests a liming effect, which can alleviate soil acidity and enhance nutrient availability, particularly phosphorus and nitrogen. Acidic soils often constrain vegetable crop productivity, and biochar application has been shown to mitigate such limitations by stabilizing soil pH (Novak *et al.*, 2014).

The observed increase in soil organic carbon under biochar treatments is consistent with previous findings that biochar contributes to long-term carbon sequestration and improves soil structural stability (Wei *et al.*, 2015). Higher organic carbon levels enhance microbial activity and nutrient cycling, thereby supporting sustained crop growth. Similarly, increased availability of soil nitrogen in biochar-treated plots indicates reduced nutrient leaching and improved nutrient retention, which are essential for root crop development (Schröder *et al.*, 2018).

Sustainability and agricultural waste utilization

The use of biochar derived from agricultural residues such as corn cobs, coconut husks, peanut shells, and sugarcane bagasse offers a dual benefit of improving crop productivity while promoting sustainable waste management. Agricultural waste disposal poses significant environmental challenges, and converting these residues into biochar provides a value-added solution that supports soil fertility and reduces environmental pollution (Yu and Wu, 2018).

From a broader perspective, the adoption of biochar-based soil amendments aligns with global efforts toward sustainable food production systems that balance productivity with environmental stewardship (Popp *et al.*, 2013; Pretty and Bharucha, 2014). The findings of this study suggest that locally available agricultural wastes can be effectively transformed into biochar to enhance soil health and carrot productivity, contributing to resilient and sustainable agricultural systems.

Implications for food security and sustainable intensification

Improved carrot yield and soil quality observed under biochar treatments have direct implications for food security, particularly in regions facing soil degradation and limited access to chemical fertilizers. Biochar-based amendments support sustainable intensification by improving yield without increasing dependence on external inputs that may negatively affect soil and water quality (Power, 2010; Pingali *et al.*, 2014).

Overall, the results demonstrate that agricultural-waste-derived biochars, especially corn cob biochar, represent a viable and environmentally sound strategy for enhancing carrot productivity and soil fertility under field conditions.

Limitations

Despite the positive effects observed, this study was limited to a single growing season and a uniform biochar application rate, which may not fully capture longer-term or cumulative impacts on soil properties and carrot productivity. In addition, detailed physicochemical characterization of the biochars was not conducted, which may have influenced variability among biochar treatments. Future multi-season field studies incorporating different application rates and comprehensive biochar characterization are necessary to strengthen the generalizability of the findings.

CONCLUSION

The present study demonstrates that biochar derived from agricultural waste significantly improves soil chemical properties, vegetative growth, and yield of carrot under field conditions. Application of biochar resulted in higher soil pH, increased organic carbon content, and enhanced nitrogen availability compared with the untreated control. These improvements in soil fertility were closely associated with superior plant growth, root development, and yield performance.

Among the biochar sources evaluated, corn cob biochar consistently produced the most pronounced positive effects, leading to greater plant height, leaf number, root diameter, and approximately 25% higher total and marketable yield compared with the control. Biochars derived from coconut husk, peanut shell, and sugarcane bagasse also improved carrot productivity, although to a lesser extent. The observed differences among biochar types highlight the importance of feedstock selection in determining biochar effectiveness.

Overall, the findings confirm that agricultural-waste-derived biochar is an effective soil amendment for enhancing carrot productivity while simultaneously improving soil health. The use of biochar offers a sustainable approach to soil management by converting locally available agricultural residues into value-added inputs that support crop production and long-term soil fertility.

RECOMMENDATIONS

Based on the findings of this study, the following recommendations are proposed:

1. Adoption in carrot production: Corn cob biochar is recommended as a soil amendment for carrot cultivation due to its superior performance in improving soil properties and yield.
2. Utilization of local agricultural residues: Farmers and agricultural practitioners should be encouraged to convert locally available agricultural wastes into biochar as a cost-effective and environmentally friendly soil management practice.
3. Rate and timing optimization: Further studies should evaluate different biochar application rates and timing to determine optimum management practices for maximizing carrot yield and soil benefits.
4. Long-term field evaluation: Long-term experiments are recommended to assess the residual effects of

biochar on soil fertility, nutrient dynamics, and crop productivity across multiple growing seasons.

5. Broader crop applicability: Future research should investigate the effectiveness of agricultural-waste-derived biochars on other root and vegetable crops to broaden their application in sustainable horticultural systems.
6. Integration with nutrient management: Combining biochar with organic or inorganic fertilizers should be explored to enhance nutrient-use efficiency and reduce fertilizer losses.

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