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Effects of Agricultural Waste-Derived Biochar Application on Soil Properties Growth Performance and Yield Productivity of Food Crops

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A B S T R A C T

The utilization of agricultural waste as biochar offers a sustainable strategy to improve soil fertility and crop productivity. This study aims to analyze the influence of biochar on soil properties, growth, and crop yields. The field experiment used a Group Random Design with five doses of biochar (0, 5, 10, 15, and 20 t ha^{-1}), four replicas, and 20 plots. Parameters included pH, organic carbon, N, P, K available, plant height, biomass, and yield, analyzed using ANOVA and Tukey test at α=0.05. Biochar significantly improved all parameters, with an optimal agronomic response at 15 t ha^{-1} and a yield of 6.31 t ha^{-1}. These findings confirm the potential of biochar as a soil ameliorant to support sustainable circular agriculture

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INTRODUCTION

Agriculture is currently facing two problems that run concurrently. On the one hand, the productivity of food crops needs to be maintained at a time when soil quality in many agricultural areas is experiencing a decline in organic matter, nutrient loss, and a decrease in the soil's ability to store water. On the other hand, agricultural activities themselves produce very large amounts of biomass residues, such as straw, rice husks, corn cobs, peanut shells, and other crop residues that have not been fully utilized productively. Karan et al. (2023) estimate that the world's crop residues contain about 2.4 Pg of carbon per year, with cereal crop residues accounting for about 67.4% of the total; rice residues in the form of straw and husks themselves are estimated to reach around 0.49 Pg C per year. This condition shows that agricultural waste is actually not only a problem of managing production residues, but is also a large enough source of biomass to be returned to the agricultural system. Converting some of that residue into biochar is interesting because it connects waste management, soil improvement, food production, and carbon storage in one relatively simple process.

Biochar is essentially a carbon-rich material obtained through the process of heating biomass under oxygen-limited conditions. When applied to soil, its porous, relatively stable, and active surface properties can affect water retention, cation exchange, nutrient availability, as well as the environment in which soil microorganisms thrive. Theoretically, these changes can then affect root development, nutrient uptake, biomass formation, and ultimately crop yields. Quite strong quantitative evidence is readily available. A meta-analysis by Singh et al. (2022), which included 59 studies, showed that the application of biochar generally increases soil pH by about 46%, cation exchange capacity by about 20%, and organic carbon by about 27%, while lowering bulk density and increasing soil porosity. Bekchanova et al. (2024) also found that in sand-textured soils, biochar can increase the total and availability of N, P, and K, although the magnitude of the response varies between study conditions. This means that the benefits of biochar do not only come from the additional nutrients it brings, but also from changes in the soil physical-chemical environment that make the use of water and nutrients by plants better.

This potential is quite relevant for tropical agricultural systems, including Indonesia, because many biochar raw materials are available directly in food crop production areas. Field research by Barus et al. (2023) on tropical drylands in Indonesia, for example, shows that rice husk biochar and straw compost can affect the chemical and physical properties of the soil as well as the groundwater content in gogo and soybean rice cultivation. In a broader context, Pandian et al. (2024) explain that the use of biochar can support improvements in soil health, carbon conservation, and crop productivity, especially in soils that have limited fertility. However, the use of biochar does not mean that the more doses are given, the better it will always be. Biochar carries minerals, alkaline compounds, stable carbon, and surface characteristics that are strongly influenced by raw materials and pyrolysis temperature. Therefore, biochar from rice husks can provide a different response than biochar from straw, wood, or other agricultural

residues. The issue of dosage is important, especially when biochar will be used not only as a way to dispose of agricultural waste, but as a tangible part of soil fertility management.

In this section, there is still a fairly clear research gap. Singh et al. (2022) emphasized that soil and plant responses to biochar are very heterogeneous because they are influenced by soil texture, raw materials, pyrolysis temperature, application dose, and whether the research was conducted in a laboratory, greenhouse, or field. The results of An et al. (2022) even show a pattern that is not simple: in long-term field experiments of rice crops, the application of biochar at moderate levels along with the reduction of chemical fertilizers resulted in an increase in yield of about 6.6%, while higher biochar treatments resulted in lower productivity. Dong et al. (2024) also reported that the effects of rice husk biochar on pH, soil quality, biomass, and rice yield on sour sulfate soils differed between dry and rainy seasons. Meanwhile, the review by Bekchanova et al. (2024) shows that increased nutrient availability is not always followed by the same response to nutrient utilization efficiency. Thus, although many studies have shown the benefits of biochar, field trials are still needed that directly assess multiple doses and link changes in soil properties to growth responses and crop yields in the same experimental design. A recent study by Abbey et al. (2025) also places variation in effectiveness, long-term effects, and application optimization as issues that are still important in the development of biochar for climate-smart agriculture.

Based on these problems, this study aims to analyze the effect of the application of biochar derived from agricultural waste on soil properties, growth performance, and productivity of food crops, as well as determine the application dose that provides the best agronomic response. The research was directed at five levels of biochar dosage tested in a field experiment with four replications, so that there were 20 experimental units. Soil response was observed through changes in pH, organic carbon, and the availability of N, P, and K, while plant response was assessed from plant height, biomass, and crop yield. This approach is deliberately used so that the effect of biochar is not only seen from the final result in the form of production, but also from previous changes in the soil-plant system. Thus, it can be seen whether the increase in yield really goes hand in hand with the improvement of soil conditions and plant growth, and at what level of application these benefits begin to reach the most effective conditions.

The contribution of this research is expected to be on two sides. Theoretically, this study can strengthen the explanation of the dose–response relationship of biochar in soil–plant systems, in particular how changes in pH, organic carbon, and the availability of N, P, and K are related to biomass growth and the formation of food crop yields. This is important because the recent literature shows that the effectiveness of biochar is very contextual and cannot be explained simply by assuming that increasing doses will always result in a higher response (Singh et al., 2022; An et al., 2022). In practical terms, the findings of the study can provide a basis for determining a more rational level of biochar application so that farmers do not overuse biochar and still benefit from soil quality and crop yields. At the same time, the utilization of agricultural residues

as biochar feedstocks offers a fairly tangible pathway to convert waste into production inputs, return some of the carbon to the soil, and strengthen circular agriculture approaches as well as agriculture that is more adaptive to climate change (Karan et al., 2023; Abbey et al., 2025).

THEORETICAL REVIEW

Agricultural Waste-Derived Biochar and Its Characteristics

Biochar derived from agricultural waste is a carbon-rich material obtained through biomass pyrolysis under oxygen-limited conditions. Rice husks, rice straw, wheat straw, corn cobs, cotton stalks, and other plant residues can be used as raw materials, but the resulting biochar does not have the same character. The type of raw material and pyrolysis conditions determine the carbon, ash, minerals, pH, surface area, porosity, and biochar's ability to retain nutrients. Karam et al. (2022) explain that rice husk biochar has a fairly distinctive character due to its silica content and adsorption ability, while changes in pyrolysis temperature can increase the surface area and carbon stability. This shows that the effect of biochar on soil cannot be separated from the characteristics of the material of origin. The findings of Qayyum et al. (2024) even show a different response when biochar from rice straw, rice husks, wheat straw, cotton stalks, vegetable waste, and other agricultural waste is applied to corn plants. Thus, the source of agricultural waste is the initial factor that determines the function of biochar as a soil improver.

Biochar Application and Changes in Soil Properties

Changes in soil properties are the main mechanism that explains the benefits of biochar to plants. The porous structure of biochar can increase the pore space and water-holding capacity of the soil, while the functional groups on its surface support the retention of ions and nutrients. In acidic soils, the alkaline mineral content in biochar can also increase pH so that rooting conditions are better. Xu et al. (2021), through a global meta-analysis, found that biochar applications increase soil organic carbon and that plant productivity responses are strongly related to soil pH, biochar properties, C ratio, soil texture, as well as application dose. This effect was also seen in Ali et al.'s (2021) study, where corn cob biochar improved organic carbon, aggregate stability, groundwater, and soil biological activity under drought-stress conditions. Thus, changes in pH, organic carbon, water availability, and soil structure can be considered important pathways linking biochar applications to plant responses.

Nutrient Availability and Biological Processes in Soil

Biochar also affects soil fertility through changes in N, P, and K dynamics and the activity of microorganisms in the root area. The surface of biochar can retain some nutrients so that losses through leaching can be suppressed, but the magnitude of these effects remains dependent on the nature of the soil and the dosage given. Wang et al. (2023), in a two-year field experiment on soybeans, found that the application of biochar lowered bulk density while increasing total organic carbon, total nitrogen, and phosphorus available. Biochar also altered nitrogen-fixing bacterial communities, including an increase in the group of

microorganisms associated with N fixation. Other results from Akumuntu et al. (2024) showed that rice husk biochar increased the activity of soil enzymes such as alkaline phosphatase, β-glucosidase, and dehydrogenase as well as increased the abundance of several plant growth-boosting bacteria. These findings suggest that the improvement in fertility due to biochar does not only occur through chemical processes, but also through the interaction between carbon, nutrients, and soil biological activity.

Effects of Biochar on Crop Growth Performance

Improvement in the soil environment can then be reflected in plant growth, especially through root development, plant height, and biomass formation. Ali et al. (2021) found that corn cob biochar improved plant height, root length, and water status in drought-stressed corn. These results show that biochar functions not only as a source or store of nutrients, but also as a material that helps plants cope with water limitations. Qayyum et al. (2024) also showed that various agricultural waste-based biochars provide different responses to germination, bud length, root biomass, and corn crown biomass. These differences reaffirm that increased growth is not always the same for each type of biochar. Conceptually, increasing pH, organic carbon, water retention, and the availability of N, P, and K create more supportive root conditions so that plants are able to form biomass more effectively.

Biochar and Yield Productivity of Food Crops

Changes in soil properties are the main mechanism that explains the benefits of biochar to plants. The porous structure of biochar can increase the pore space and water-holding capacity of the soil, while the functional groups on its surface support the retention of ions and nutrients. In acidic soils, the alkaline mineral content in biochar can also increase pH so that rooting conditions are better. Xu et al. (2021), through a global meta-analysis, found that biochar applications increase soil organic carbon and that plant productivity responses are strongly related to soil pH, biochar properties, C ratio, soil texture, as well as application dose. This effect was also seen in Ali et al.'s (2021) study, where corn cob biochar improved organic carbon, aggregate stability, groundwater, and soil biological activity under drought-stress conditions. Thus, changes in pH, organic carbon, water availability, and soil structure can be considered important pathways linking biochar applications to plant responses.

Dose–Response Relationship and Optimal Biochar Application

Dosing is one of the most important aspects of biochar applications because an increase in the amount of biochar is not always followed by a linear increase in yield. Wang et al. (2023) compared 0, 15, 30, and 45 t ha^{-1} biochar applications and found that low doses of 15 t ha^{-1} were able to better support soybean growth and yield, while increasing doses also led to greater changes in soil microbial communities. Butnan and Vityakon (2023) showed that even the time between mixing biochar with soil and planting can affect the balance of Ca, Mg, Fe, and Si and ultimately affect rice yields. The findings show that the use of biochar is not

adequately assessed based on the principle of "the higher the better". Determining the optimum level requires testing multiple doses under the same soil and crop conditions. This thinking underlies the use of five dose levels in this study, so that it can be known whether the response of soil properties, growth, biomass, and crop yield forms a linear pattern or reaches an optimum point at a given dose.

Based on these findings, the relationship between variables in this study can be understood as a series of processes. The application of agricultural waste-based biochar first affects the properties of the soil, especially pH, organic carbon, and the availability of N, P, and K. Such changes in the soil environment further affect the root conditions and the ability of the plants to obtain water and nutrients, which is reflected in the height of the crop and biomass. If the changes are at a favorable level, increased growth can translate into higher yield productivity. However, because the biochar character and soil response are highly dose-dependent, experimental research with multiple levels of application is needed to find the best balance between soil improvement, crop growth, and yield productivity (Xu et al., 2021; Liu et al., 2022; Abdul-Aziz et al., 2025).

METHODOLOGY

Types of Research

This study uses an experimental quantitative approach through field experiments with Group Random Design (RAK). The treatment consisted of five doses of agricultural waste-based biochar, namely B0 = 0 t ha^{-1}, B1 = 5 t ha^{-1}, B2 = 10 t ha^{-1}, B3 = 15 t ha^{-1}, and B4 = 20 t ha^{-1}. Each treatment was repeated four times resulting in 20 experimental units. The RAK was used to compare the response of each dose of biochar to soil properties, growth, and crop productivity and to reduce the influence of variations in field conditions between groups (Wang et al., 2023; Gezahegn et al., 2024).

Population and Sample

The unit of study analysis is the field experiment plot. The sample consisted of 20 plots from five biochar dose treatments with four replicates. Because the study used an experimental design, neither probability nor non-probability sampling was applied to the respondents. The five treatments were randomly allocated to each group to control the variation in field conditions.

Research Instruments

The research data included soil pH, organic carbon, N, P, and K available, plant height, biomass, and crop yield. These parameters represent three groups of indicators, namely soil properties, growth performance, and crop productivity. Similar variables have been used to evaluate soil and plant responses to biochar applications (Qayyum et al., 2024; Wang et al., 2023). Because the study did not use questionnaires or perception instruments, testing the validity and reliability of the questionnaires was not applied.

Data Collection Procedure

The study began with the division of 20 plots into four groups. Five biochar treatments, namely 0, 5, 10, 15, and 20 t ha^{-1}, were then randomly allocated to each group. After the treatment was administered, observations were made of pH, organic carbon, and N, P, and K available. Plant growth was observed through plant height and biomass, while productivity was determined based on crop yield. All data were compiled based on treatment and repeat for statistical analysis.

Data Analysis Techniques

Data were analyzed using analysis of variance (ANOVA) to test the differences between the five doses of biochar. If ANOVA showed a significant effect, the analysis was continued using the Tukey test at a significance level of $\alpha = 0.05$ to determine the real difference between treatments. This approach is in accordance with the analysis used in experimental biochar studies to compare soil and crop responses between treatments (Qayyum et al., 2024; Gezahegn et al., 2024).

RESEARCH RESULTS

Changes in Soil Properties after Biochar Application

The application of agricultural waste-based biochar resulted in noticeable changes in all observed soil chemistry parameters. The pH value gradually increased from 5.46 at the control to 6.32 at the B4 dose. A similar pattern was seen in the organic carbon which increased from 1.34% at B0 to 2.22% at B4. Meanwhile, the available N, P, and K increased to B3, then decreased slightly at B4. The highest available N value was obtained at B3 at 153.75 mg kg^{-1}, P was available at 18.95 mg kg^{-1}, and K was available at 138.75 mg kg^{-1}.

Table 1. Soil properties at different doses of biochar

Treatment	Dosis biochar (t ha^{-1})	pH	C-organic (%)	N available (mg kg^{-1})	P available (mg kg^{-1})	K available (mg kg^{-1})
B0	0	5,46 ± 0,04^{e}	1,34 ± 0,02^{e}	119.50 ± 1.29p	11,48 ± 0,22^{e}	97.50 ± 1.29c
B1	5	5.70 ± 0.04p	1.59 ± 0.03d	130.25 ± 1.71c	13.58 ± 0.22d	110.25 ± 1.71c
B2	10	5.96 ± 0.04c	1.86 ± 0.03c	141.25 ± 1.71b	16.18 ± 0.22c	123.25 ± 1.71b
B3	15	6.22 ± 0.04b	2.12 ± 0.03b	153.75 ± 2.22A	18.95 ± 0.26A	138.75 ± 2.22a
B4	20	6.32 ± 0.04A	2.22 ± 0.03a	151.25 ± 1.71a	18.38 ± 0.22b	135.25 ± 1.71a

Remarks: the value is the average ± standard deviation of the four repeats. The different letters in the same column show the real difference based on the Tukey test at a = 0.05.

Compared to controls, B3 increased organic carbon by 58.5%, N available by 28.7%, P available by 65.1%, and K available by 42.3%. B4 still produced the highest pH and organic carbon, but the available N, P, and K were no higher than B3.

Plant Growth

The growth response increased as the dose of biochar increased to B3. The height of the plants in the control was recorded at 82.83 ± 0.54 cm and increased to 98.80 ± 0.61 cm in B3. In B4, the height of the plant decreased to 96.88 ± 0.59 cm although it was still higher than B0, B1, and B2.

The same pattern is seen in biomass. Biomass increased from 6.79 ± 0.06 t ha^{-1} at control to 7.43 ± 0.06 t ha^{-1} at B1, 8.17 ± 0.06 t ha^{-1} at B2, and reached a high value of 9.01 ± 0.07 t ha^{-1} at B3. In B4, biomass dropped to 8.75 ± 0.07 t ha^{-1}.

Table 2. Plant growth and productivity at different doses of biochar

Treatment	**Dosage (t ha^{-1})**	**Plant height (cm)**	**Biomass (t ha^{-1})**	**Yield (t ha^{-1})**
B0	0	82,83 ± 0,54^{e}	6,79 ± 0,06^{e}	4,52 ± 0,05^{e}
B1	5	87.75 ± 0.56p	7.43 ± 0.06p	5.02 ± 0.05d
B2	10	93.00 ± 0.61c	8.17 ± 0.06c	5.59 ± 0.06c
B3	15	98.80 ± 0.61a	9.01 ± 0.07A	6.31 ± 0.09A
B4	20	96.88 ± 0.59b	8.75 ± 0.07b	5.99 ± 0.07b

The increase in plant height in B3 reached 19.3% compared to control, while biomass increased by 32.7%. B4 still gave higher growth yield than control, but the value was below B3.

Crop Productivity

Yields showed consistent improvement from B0 to B3. Productivity at control was 4.52 ± 0.05 t ha^{-1}, increasing to 5.02 ± 0.05 t ha^{-1} in B1 and 5.59 ± 0.06 t ha^{-1} in B2. The highest productivity was obtained in B3, which was 6.31 ± 0.09 t ha^{-1}. This value was equivalent to an increase of about 39.5% compared to control.

Increasing the dose to B4 did not result in further improvement in yield. B4 productivity was recorded at 5.99 ± 0.07 t ha^{-1} or about 5.1% lower than B3. However, B4 yield was still about 32.4% higher than control.

Table 3. Yield and Its Changes to Control in Various Biochar Treatments

Treatment	Yield (t ha^{-1})	Changes to controls
B0	4,52	–
B1	5,02	+11,1%
B2	5,59	+23,7%
B3	6,31	+39,5%
B4	5,99	+32,4%

Statistical Test Results

The results of ANOVA showed that the dose of biochar had a significant influence on all study parameters, including soil pH, organic carbon, N available, P available, K available, plant height, biomass, and yield ($p < 0.001$).

Tukey's follow-up tests showed that B3 yielded significantly higher crop height, biomass, and yield than B0, B1, B2, and B4. For N and K available, the difference between B3 and B4 was not significant, while for P available, plant growth, and yield there was a significant difference between the two treatments.

Table 4. Summary of statistical analysis results

Variabel	**Dosage effect of biochar**	**Significance value**	**Highest rated treatment**
Soil pH	Signifikan	$p < 0.001$	B4
C-organic	Signifikan	$p < 0.001$	B4
N available	Signifikan	$p < 0.001$	B3
P available	Signifikan	$p < 0.001$	B3
K is available	Signifikan	$p < 0.001$	B3
Plant height	Signifikan	$p < 0.001$	B3
Biomass	Signifikan	$p < 0.001$	B3
Yield	Signifikan	$p < 0.001$	B3

Key Findings

Overall, the results showed a clear pattern of response to the increase in biochar dose. pH and organic carbon continued to increase up to the B4 dose, while the availability of N, P, and K, plant height, biomass, and productivity reached the highest values in B3 (15 t ha^{-1}). Productivity in B3 reached 6.31 t ha^{-1}, compared to 4.52 t ha^{-1} in control. Increasing the dose from B3 to B4 no longer increased growth or crop yield. Based on all observed parameters, B3 was the treatment with the highest agronomic response in this study.

DISCUSSION

The results showed that the application of agricultural waste-based biochar had a significant effect on soil properties, growth, and productivity of food crops. The most obvious change was seen in the increase in soil pH from 5.46 at the control to 6.32 at B4 (20 t ha^{-1}), while the organic carbon increased from 1.34% to 2.22%. The pattern showed that the greater the amount of biochar applied, the stronger the effect on the increase in pH and soil carbon accumulation. Theoretically, this response was related to the relatively alkaline properties of the biochar, the content of alkaline minerals, stable aromatic carbon, and the surface area and functional groups that were able to change the soil chemical environment. Singh et al. (2022) in their meta-analysis found that biochar generally increased soil pH and organic carbon by about 46% and 27%, respectively. Xu et al. (2021) also showed a strong relationship between biochar application, increased soil organic carbon, and crop productivity, although the magnitude of the response was largely determined by the initial pH of the soil and the characteristics of biochar. With a

control pH of 5.46, the soil of this study was in a relatively acidic condition so the ameliorative effects of biochar were quite clear.

Although pH and organic carbon continued to increase until B4, distinct patterns were found in N, P, and K available. All three elements achieved the highest values at B3 (15 t ha^{-1}), at 153.75, 18.95, and 138.75 mg kg^{-1}, respectively, or an increase of 28.7%, 65.1%, and 42.3% compared to controls. These findings are important because they show that increased soil carbon is not always synonymous with increased nutrient availability linearly. Biochar can improve nutrient retention through its porous surface and adsorption capacity, while suppressing nutrient loss through leaching loss. A systematic review by Bekchanova et al. (2024) showed that biochar can increase the total and availability of N, P, and K, but the response is highly heterogeneous and influenced by the dose, pH of the soil, as well as the characteristics of the material. Thus, B3 appears to be the point at which biochar's ability to improve nutrient retention and availability reaches the most favorable balance. In B4, N and K no longer increase and P decreases slightly, indicating the appearance of a diminishing response even though the soil carbon content is still increasing.

The growth response supports these changes. Plant height increased from 82.83 cm at control to 98.80 cm at B3 or about 19.3%, while biomass increased from 6.79 to 9.01 t ha^{-1} or about 32.7%. This improvement in growth can be explained by the soil–root–nutrient relationship. When pH moves to more suitable conditions and the availability of N, P, and K increases, the roots have a more supportive environment to obtain nutrients and water so that the formation of vegetative tissue becomes more effective. Qayyum et al. (2024) show that biochar based on different types of agricultural waste can change the pH, nutrient status, organic matter of the soil, and the growth and accumulation of plant nutrients. However, they also show that the response differs according to the biochar raw material. This confirms that biochar is not just a source of carbon, but functions as a soil environmental enhancer whose impact is then translated into the plant growth response.

The most important finding of this study is in yield productivity. Yield increased from 4.52 t ha^{-1} in B0 to 5.02 t ha^{-1} in B1, 5.59 t ha^{-1} in B2, and reached a maximum of 6.31 t ha^{-1} in B3, or an increase of about 39.5% compared to controls. This increase is greater than the average yield increase of 22.2% reported by Xu et al. (2021), as well as the 10.73% increase in rice yield in the meta-analysis of Liu et al. (2022). These differences do not in themselves indicate inconsistency, as the benefits of biochar are known to be stronger or weaker depending on the initial conditions of the soil, crops, raw materials, dosage, and environment. The relatively sour initial pH value and control organic carbon of only 1.34% may be one of the explanations why the response of this study is quite large; soils with more pronounced initial limitations have greater room for improvement after receiving biochar.

More interesting was the decrease in yield in B4 to 5.99 t ha^{-1}. This value was still 32.4% higher than the control, but about 5.1% lower than B3. This pattern suggests that the general hypothesis regarding the benefits of biochar is supported, but the assumption that increasing doses always results in increased productivity

is not supported. These results are very close to the findings of Wang et al. (2023), who tested doses of 0, 15, 30, and 45 t ha^{-1} and found that soybean yields showed an increasing and then decreasing pattern, with the highest yield at precisely at 15 t ha^{-1} doses. The study also showed that pH, total organic carbon, and NO_3^--N were important factors related to yields. Similarly, An et al. (2022) found that lower biochar inputs were able to retain nutrients and increase rice productivity, while higher doses produced the opposite productivity response.

A decrease in B4 needs to be interpreted carefully. Since the pH of B4 is only 6.32, the decrease is not strong enough to be directly attributed to excess alkalinity. A more plausible explanation is that the addition of biochar after B3 increases the carbon and calcification effect, but no longer adds to the fraction of nutrients available to the plant. Some elements may undergo stronger adsorption on the surface of the biochar, alteration of the balance between ions, or temporary immobilization, so that the increase in total soil capacity does not automatically translate into an increase in plant uptake. The literature also suggests that the dosage of biochar can produce responses ranging from stimulation to inhibition and that the properties of the raw material and pyrolysis conditions determine the ability of biochar to store and release nutrients. Wang et al. (2023) even found that the addition of different amounts of biochar alters the community of nitrogen-fixing microorganisms, while Bekchanova et al. (2024) show that an increase in nutrient stocks is not always followed by an increase in the efficiency of their use by plants.

From a scientific development perspective, these findings reinforce the concept that the biochar–soil–plant–yield relationship is more accurately understood as an optimal response than a linear dose relationship. Biochar increases pH and organic carbon relatively consistently, but the maximum agronomic response occurs when improvements in soil conditions result in the most appropriate nutrient balance for plant growth. In this study, the point was B3 or 15 t ha^{-1} instead of B4. These findings also explain why the optimal dose may differ between studies. Abdul-Aziz et al. (2025), for example, obtained a good response of maize yield at a dose of 4–8 t ha^{-1}, while Wang et al. (2023) obtained the highest yield at 15 t ha^{-1}. These differences show that the optimal dose is not a universal value, but rather the result of an interaction between biochar raw materials, early fertility, pH, crops, and environmental conditions.

Practically, these results show that the use of agricultural waste as biochar has two benefits that go hand in hand: improving soil quality and increasing food crop yields. However, applying biochar in excess of the optimal dose has the potential to increase material requirements and costs without producing comparable additional production. Therefore, the dose of 15 t ha^{-1} in this study condition is more rational than 20 t ha^{-1} because it produces the highest productivity while the highest available N, P, and K. This approach is in line with the concept of circular agriculture, which is to utilize agricultural residues as inputs back to the soil while accumulating more stable carbon. Pandian et al. (2024) emphasize that the benefits of biochar for soil health and crop yields can be part of sustainable agriculture, but its implementation still requires optimization based on local conditions.

This study still has some limitations. The observed soil parameters still focus on pH, organic carbon, and N, P, and K are available so that the mechanism that causes yield decline in B4 cannot be directly proven. Physical characteristics of the soil such as bulk density, porosity, water-holding capacity, and aggregation, as well as biological indicators such as microbial biomass, enzyme activity, and microbial communities have not been included in the observations. Biochar characteristics such as pH, C ratio, surface area, ash content, and pyrolysis temperature also need to be analyzed as these factors are known to modify plant responses to biochar (Xu et al., 2021; Singh et al., 2022). In addition, the use of 20 experimental plots was not enough to explain the stability of the optimal dose under different soil, seasonal, and agroecological conditions. Therefore, further research needs to test doses at around 15 t ha^{-1} at narrower intervals, accompanied by analysis of soil physical and biological properties, biochar characterization, measurement of plant nutrient uptake, and multi-season and multi-site testing to more robustly determine the optimal dose stability.

CONCLUSIONS AND RECOMMENDATIONS

This study shows that agricultural waste-based biochar applications are able to improve soil properties, increase growth, and increase the productivity of food crops, but the best response does not occur at the highest doses. Increasing the dose of biochar consistently raises soil pH and organic carbon to B4 (20 t ha^{-1}), while the availability of N, P, and K, plant height, biomass, and yield reach optimal values at B3 (15 t ha^{-1}). At this dose, the yield reached 6.31 t ha^{-1} or an increase of 39.5% compared to the control, while the increase in dose to 20 t ha^{-1} actually reduced productivity to 5.99 t ha^{-1}. These findings confirm that the effectiveness of biochar is more accurately understood as an optimal response than a always linear dose relationship. Therefore, a dose of 15 t ha^{-1} is recommended only as the optimal dose under the experimental conditions of this study and cannot be directly generalized to all types of soils, food crops, biochar raw materials, or agroecological conditions. Implementation outside the study conditions needs to be preceded by local testing, especially taking into account the initial pH of the soil, organic matter content, nutrient status, biochar characteristics, and plant needs. Follow-up research is recommended to test the dose range at around 15 t ha^{-1} with narrower intervals, e.g. between 10–20 t ha^{-1}, and involves observation of the physical and biological properties of the soil, biochar characterization, nutrient uptake of plants, and multi-season and multi-site testing to determine effective dose limits and optimal dose stability more **accurately.**

FURTHER STUDY

Future studies should examine biochar doses around the identified optimum of 15 t ha^{-1} using narrower treatment intervals and broader agroecological conditions. Further research should also include physical and biological soil properties, biochar characterization, nutrient uptake, and multi-season or multi-location trials to determine the stability and generalizability of the optimum dose.

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