

RESEARCH ARTICLE OPEN ACCESS

Effects of Wastewater Filtration on the Properties of Rice Husk Biochar and Its Reuse as Soil Amendment After Wastewater Filtration

Edna Buhnyuy Visiy¹  | Teikeu Assatse William¹ | Demba Aissata Samoura²  | Asi Quiggle Atud¹  | Abasiama Sunday Umoren³ 

¹Department of Environmental Engineering, National Advanced School of Public Works, P. O. Box 510, Yaoundé, Cameroon | ²Department of Natural Resource Management, Faculty of Sciences and Techniques, University of N'Zérékore, N'Zérékore BP 50, Guinea | ³Department of Environmental Management, Federal University of Technology, Akure, Ondo State, Nigeria

Correspondence: Edna Buhnyuy Visiy (visiyedna@gmail.com)

Received: 3 September 2024 | **Revised:** 20 May 2026 | **Accepted:** 21 May 2026

Academic Editor: Claudio Cocozza

Keywords: *Lactuca sativa* | lettuce growth | nutrient enrichment | rice husk biochar | soil amendment | wastewater filtration

ABSTRACT

Biochar is valued for its soil-enhancing properties but often shows limited benefits for crop production due to low inherent nutrient content. Combining biochar with fertilizers or manures can greatly improve its effectiveness. This study explored the potential of enriching rice husk biochar (RHB) with nutrients by using it as a filter medium in domestic wastewater treatment. The agronomic effects of the treated rice husk biochar (TRHB) were then compared to those of the pristine RHB in a screenhouse pot trial at the University of Dschang, Cameroon. RHB and TRHB were applied at 10, 20, and 30 t/ha, with and without mineral fertilizer in a completely randomized design with four replications. Agronomic effects on lettuce (*Lactuca sativa*) were evaluated over two cropping cycles by measuring the number of leaves, leaf surface area, shoot height, and aboveground biomass. Wastewater filtration significantly altered biochar properties. Compared to RHB, TRHB showed increases in bulk density (+45.1%), organic carbon (+21%), total nitrogen (+170%), and total phosphorus (+106.7%). However, there was a decrease in the pH (−29.4%), ash content (−27.9%), cation exchange capacity (−10%), and base cations (K: −49.8%, Na: −44.6%, Ca: −22.2%, Mg: −13.6%). In unfertilized treatments, TRHB increased aboveground biomass relative to the control (up to 87.9% and 244.1% at 30 t/ha in the first and second cycles, respectively), but these gains were not statistically significant at rates below 30 t/ha. In contrast, RHB produced significantly higher aboveground biomass increases of 337.7% and 436.4% at 30 t/ha. Fertilization significantly enhanced aboveground biomass production ($p < 0.05$) across treatments. Although wastewater filtration achieved partial nutrient enrichment, the substantial loss of ash and base cations reduced the liming capacity and overall agronomic performance of TRHB compared to RHB on the acidic oxisol. These findings highlight the trade-offs in dual-use biochar systems and the need for optimized filtration strategies to enhance its value as a sustainable soil amendment.

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Copyright © 2026 Edna Buhnyuy Visiy et al. *Applied and Environmental Soil Science* published by John Wiley & Sons Ltd.

1 | Introduction

Soil degradation and nutrient depletion pose significant challenges in agriculture, highlighting the need for innovative solutions to sustain soil fertility and support sustainable crop production. Biochar, a solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment [1], has gained attention for its potential to enhance soil health due to its unique properties, notably its porous structure, large internal surface area (200–1000 m²/g), and low bulk density (less than 0.6 g/cm³) [2, 3]. These properties have made biochar more attractive for use as a soil amendment [4–6] and as a wastewater filtration media [2, 7, 8]. Additionally, biochar contributes to carbon sequestration due to its high chemical stability [9, 10]. However, the properties of the biochar will greatly depend on the feedstock type and conditions of pyrolysis, such as the pyrolysis temperature, heating rate, and oxidation capacity [11]. Biochar derived from cellulosic feedstocks, such as straw or wood, often has low ash content and thus lacks essential nutrients, such as calcium, magnesium, potassium, and trace elements, such as iron, zinc, and manganese [12]. Also, biochars produced at lower temperatures (< 500°C) favor nutrient retention and water-holding capacity and are hence suitable for agriculture, while higher temperatures enhance adsorption capacity and chemical stability, making it more suitable for wastewater treatment [9, 10].

Various biomass, notably crop residues, woody materials, green wastes, animal manures, and agricultural byproducts, can be used as feedstocks for biochar production [9]. Using agricultural wastes for biochar production offers an added advantage as it promotes the management of these wastes as they are most often underutilized due to low heating value and slow decomposition rates. As a result, they are frequently disposed of by burning in fields, dumping in rivers, or piling near processing facilities, leading to soil degradation and environmental pollution [4, 13]. Among these agricultural wastes, rice husk is prominent due to the high global rice consumption rates. Rice is a staple food for more than 50% of the world's population, with the annual global production of rice husk estimated to be approximately 148.4 and 156.4 million tons in 2014 and 2018, respectively [9]. The extensive generation of rice husk, often burned near processing sites, exacerbates environmental pollution [4, 14]. Converting rice husk into biochar represents an effective strategy for promoting sustainable agriculture and mitigating environmental impact.

Rice husk biochar (RHB) has demonstrated effectiveness both in wastewater filtration [7, 15–18] and as a soil amendment [9, 19–21]. Biochar from rice husk was shown to bring more returns (33.06%) to farmers compared to corncob biochar (13.32%) and no biochar application (8.14%) when used in cassava production [20]. Additionally, studies conducted by Upadhyay et al. [22] on the influence of green waste biochar on the productivity of lettuce showed that 30 t/ha of this biochar was most effective for optimal growth of the plant in sand culture. However, the low nutrient content of biochar has limited its standalone effectiveness as positive effects of biochar application to soils are generally only observed when biochar is used together with fertilizers or manure [6, 10, 23].

Recent research has focused on methods to enhance the nutrient content of biochar in order to make it more beneficial in

agriculture [6, 10]. Techniques for producing nutrient-enriched biochar include direct pyrolysis of nutrient-rich feedstocks, such as manures, sludge, composts, and algae [24–26]; prepyrolysis treatments, such as impregnating biomass with nutrient solutions or inorganic salts before pyrolysis [27–29] and postpyrolysis treatments, which involve soaking or mixing the produced biochar with nutrient-rich liquids or fertilizers to promote nutrient adsorption [6, 30, 31]. Most of these treatments have relied on synthetic loading typically involving the direct addition of nutrient solutions to pristine biochar under controlled or room temperature conditions [32], which does not reflect the more complex and variable conditions encountered during actual wastewater treatment processes. Attempts to enrich biochar with nutrients through real wastewater filtration have yielded inconsistent and variable results [17, 33]. While some nutrient adsorption occurs, it is often incomplete and accompanied by leaching of other essential nutrients. It is therefore unclear whether biochars used as filter media in wastewater treatment can actually become enriched with plant-available nutrients in sufficient quantities to substitute or supplement conventional fertilizers. This remains a key knowledge gap, particularly in low-resource settings where resource-efficient, low-cost fertilizers are urgently needed. This study aims to contribute to the literature by investigating the potential for enriching RHB during domestic wastewater treatment and exploring its subsequent use as a nutrient-rich fertilizer for soil amendment. We hypothesized that biochars used as filter media in wastewater treatment can become nutrient-enriched and subsequently serve as an effective fertilizer for soil amendment. By integrating these two applications, this research seeks to advance sustainable agricultural practices and innovative wastewater management strategies.

2 | Materials and Methods

2.1 | Biochar Production

The rice husk (Figure 1a) used in this study was sourced from AFRIFOOD, a rice processing company in Bafoussam, West Region of Cameroon. The rice husk was pyrolyzed using a locally fabricated, batch-type metal kiln located at the University of Dschang, Cameroon. The kiln is externally fueled using firewood. During operation, the pyrolyzer unit is sealed to maintain oxygen-limited conditions necessary for pyrolysis. However, an aeration pipe was provided to capture and redirect pyrolysis gases back to the heating chamber, where they get combusted and contribute to heating. Based on preliminary experiments, the pyrolysis was conducted for 4 h (excluding cooling time) to ensure complete conversion of the feedstock. Kiln temperatures were monitored every 30 min with a thermocouple equipped with a type K probe. Temperatures in the kiln varied between 393°C and 618°C, with an average of 502°C. The resulting biochar (Figure 1b) was fine and did not require additional crushing.

2.2 | Wastewater Filtration

The RHB used in the study was previously used as a filter material for domestic wastewater treatment in our previous study [7]. This was carried out using a vertical flow filter vegetated with the macrophyte *Echinochloa pyramidalis* and replicated three times. The wastewater was passed through the system continuously for a period of 6 months at a hydraulic loading rate of



FIGURE 1 | Rice husk used for the study: before pyrolysis (a) and after pyrolysis (b).

about 350 L/m²/day. Each system featured a treatment layer consisting of a bottom gravel layer (20 cm), a biochar layer (45 cm), and a top gravel layer (5 cm). Table 1 presents the average influent and effluent characteristics of the domestic wastewater filtered using the RHB.

2.3 | Setup and Location of the Experimental Pot Trial

The pot experiment was carried out in a screenhouse environment at the University of Dschang, Cameroon, for a period of three months, from March to May 2022 corresponding to 2 growth cycles for transplanted lettuce. The region features an equatorial climate with two distinct seasons: a dry season from mid-November to mid-March and a rainy season from mid-March to mid-November. The soil used for the study was an oxisol with the following characteristics: clay = 14%, silt = 9%, sand = 77%. pH = 5.5; bulk density = 0.949 g/cm³, organic matter = 7.95%; organic carbon = 4.61%; available phosphorus (Bray II) = 34.51 mg/kg, total nitrogen = 0.38%; potassium = 2.60 meq/100g; calcium = 15.41 meq/100g; magnesium = 1.87 meq/100g; sodium = 0.74 meq/100g; CEC pH7 = 27 meq/100g.

TABLE 1 | Influent and effluent characteristics of the wastewater treatment (mean ± standard deviation, *n* = 6).

Parameter	Unit	Influent	Effluent
pH	[–]	7.8 ± 0.2	7.3 ± 0.3
EC	(μs/cm)	2653 ± 1311	1557 ± 1134
TDS		1347 ± 689	777 ± 563
TSS		210 ± 156	22.9 ± 11
NO ₃ [–]	(mg/L)	8.5 ± 9.3	8.4 ± 11.4
PO ₄ ^{3–}		36.3 ± 21.3	8.0 ± 1.8
COD		540 ± 509	141.9 ± 120.9
BOD ₅		124.8 ± 54	19.6 ± 16.8
Fecal coliforms	(log10 CFU/100 mL)	7.4 ± 0.2	5.9 ± 0.8
Fecal streptococci		6.9 ± 0.2	5.8 ± 0.5

The study involved the use of 2 biochar types: the pristine RHB and that obtained after wastewater treatment hereby referred to as treated rice husk biochar (TRHB). The experiment was carried out over 2 cropping cycles using 3 biochar application rates (10, 20, and 30 t/ha) with bare soil used as control. The biochar application rates were achieved, respectively, by mixing the following percentages of biochar with soil: 0.42%, 0.84%, and 1.26% (kg of biochar per kg of soil) based on soil bulk density of 0.949 g/cm³ assuming a plow depth of 25 cm. The treatments were as follows: T1: bare soil (B0); T2: 10 t/ha RHB (RHB10); T3: 10 t/ha TRHB (TRHB10); T4: 20 t/ha RHB (RHB20); T5: 20 t/ha TRHB (TRHB20); T6: 30 t/ha RHB (RHB30); T7: 30 t/ha TRHB (TRHB30). Each of the seven treatments was tested with and without fertilizer application, with each combination replicated four times, resulting in a total of 56 pots per trial. Fertilized treatments were indicated by appending an “F” to the corresponding treatment name. The experiment was carried out in plastic pots (20 cm in diameter and 25 cm in height) using a completely randomized design (CRD).

Soil samples were collected from the plow layer (0–25 cm) of experimental fields at the Faculty of Agronomy and Agricultural Sciences, University of Dschang, Cameroon. For each treatment, 3 kg of soil was mixed with the designated biochar before being placed into plastic pots. Fertilizer application occurred on the soil surface after transplanting. The fertilizer used was a granular 20-10-10 (N-P₂O₅-K₂O) composite, applied at a rate of 200 kg/ha in accordance with local practices. The experiment was conducted under natural rainfed conditions.

Lettuce plants (*Lactuca sativa*) were nursed for 6 weeks, and well-established seedlings with 3 true leaves were transplanted into pots, one plant per pot. Lettuce has a loose-leaf growth habit, characterized by leaves that are loosely bunched and curly, with a growth period of 65–130 days after sowing, depending on the growing season. Lettuce was selected for this study because it is known to be highly responsive to nutrients [22] making it ideal for evaluating the effects of biochar. Additionally, lettuce is recommended by the International Biochar Initiative for germination tests of biochar materials [34].

2.4 | Assessment of Plant Growth and Productivity

To assess plant growth and productivity, the number of leaves, leaf surface area, shoot height, and aboveground biomass were measured. The number of leaves was counted weekly after transplanting, while leaf surface area, shoot height, and aboveground biomass were recorded at harvest, which occurred 6 weeks post-transplanting. Leaf surface area was calculated by multiplying the length by the width of each leaf, with the length determined by averaging the north–south measurements of three fully extended leaves and the width by averaging the east–west dimensions at the widest point of each leaf. For aboveground biomass assessment, plants were cut at the soil surface, and the fresh weight of the aboveground biomass was recorded.

2.5 | Soil and Biochar Characterization

The biochar's physicochemical properties were measured before and after wastewater filtration to determine the impact of filtration on its characteristics. All analyses were conducted at the Laboratory of Soil Science and Environmental Chemistry, University of Dschang, Cameroon, using standard methods [1]. The biochar sample analyzed before wastewater filtration was a composite, prepared by mixing subsamples from each of the seven biochar batches produced. The postfiltration sample was a composite obtained by mixing subsamples from each of the three filters used during the wastewater filtration process. Additionally, the soil used in the experiment was analyzed before the study at the Laboratory of Soil Science, University of Dschang, following the standard methods outlined in Pauwels et al. [35].

2.6 | Statistical Analysis

All statistical analyses were conducted using SPSS software Version 23. To determine the significance of treatment effects, analysis of variance (ANOVA) was applied using the least significant difference (LSD) test, with a threshold set at $p < 0.05$ and the Tukey test used for post hoc comparisons. Data were analyzed separately for the first and second crop cycles to account for any temporal variations while making distinctions between fertilized and unfertilized treatments within each crop cycle. This approach ensured a comprehensive evaluation of the effects of biochar and fertilizer treatments on plant growth and productivity across both cycles.

3 | Results

3.1 | Influence of Wastewater Treatment on the Characteristics of Biochar

Table 2 presents the physicochemical properties of RHB before and after wastewater filtration (TRHB), along with the percentage changes. Wastewater filtration resulted in notable increases in several parameters: bulk density (+45.1%), organic carbon (+21%), total nitrogen (+170%), and total phosphorus (+106.7%). In contrast, significant decreases were observed in pH (from 8.5 to 6.0, −29.4%), porosity (−4.4%), ash content (−27.9%), cation exchange capacity (−10%), and several base cations (Ca: −22.2%, K: −49.8%, Mg: −13.6%, Na: −44.6%). These changes suggest that while some nutrient enrichment occurred during wastewater filtration, substantial leaching of ash and exchangeable bases also took place. This variation in properties

between RHB and TRHB is likely to influence the effectiveness of the treated biochar when reused as a soil amendment.

3.2 | Effect of Biochar Application on Plant Growth and Productivity

3.2.1 | Effect on the Number of Leaves

In the first crop cycle, the number of leaves increased progressively across all treatments over the 6-week period. No significant differences were observed among treatments during the first and second weeks. Significant differences ($p < 0.05$) emerged from the third week onward, with plants grown in RHB treatments producing more leaves than those in TRHB and control treatments (Figure 2). At harvest, the unfertilized control produced the lowest number of leaves (8), while RHB30 produced the highest (13) among unfertilized treatments, representing a 62.5% increase compared to the control. Fertilization significantly ($p < 0.05$) increased leaf number across treatments. The highest value was recorded in RHB30 + F (16 leaves), representing a 77.8% increase compared to the fertilized control (9 leaves). However, TRHB10 + F produced the lowest (8 leaves), though statistically similar to the fertilized control. In the second crop cycle, significant differences appeared earlier (from the second week). At harvest, the unfertilized control again had 8 leaves, while RHB30 + F recorded the highest number (16 leaves). Figure 2 shows the variation in the number of leaves by treatment at harvest for both crop cycles.

3.2.2 | Effect on Leaf Surface Area

Leaf surface area increased with biochar application rate for both fertilized and unfertilized plants in both cropping cycles (Figure 3). In the first crop cycle, no significant differences were observed among unfertilized treatments. Fertilization had a significant effect ($p < 0.05$), with RHB20 + F producing the largest leaf surface area (238.6 cm²), representing a 126.8% increase compared to the fertilized control (105.2 cm²) (Figure 3). In contrast, the fertilized control (B0 + F) recorded the smallest leaf surface area.

In the second crop cycle, significant differences ($p < 0.05$) were observed among fertilized treatments. RHB30 + F produced the largest leaf surface area (204.7 cm²), which was 498.5% higher than the fertilized control (34.2 cm²). Overall, leaf surface area was considerably larger in the first cropping cycle than in the second. While leaf surface area generally increased with biochar application rate, only RHB at 30 t/ha showed significant improvement compared to the control in unfertilized conditions. Figure 3 illustrates the variation in leaf surface area by treatment at harvest for both crop cycles.

3.2.3 | Effect on Shoot Height

Generally, plant height followed the trend RHB > TRHB > B0 in both cropping cycles. Shoot height increased with increasing biochar application rate for both fertilized and unfertilized plants (Figure 4). No significant differences in shoot height were observed between the two crop cycles. In the first crop cycle, fertilization significantly ($p < 0.05$) influenced plant height. The tallest plants were recorded in RHB20 + F (24.1 cm), representing a 66.2% increase compared to the fertilized control (14.5 cm) (Figure 4). In contrast, the shortest plants were in the fertilized control (B0 + F).

TABLE 2 | Changes in biochar properties following wastewater filtration.

Parameters	Pristine biochar (RHB)	Filter biochar (TRHB)	% change
Bulk density (g/cm ³)	0.255	0.370	45.1
Total porosity (%)	90	86	−4.4
pH water	8.5	6.0	−29.4
Calcium (mg/100g)	360	280	−22.2
Potassium (mg/100g)	601	302	−49.8
Magnesium (mg/100g)	535	462	−13.6
Sodium (mg/100g)	186	103	−44.6
CEC - pH7 (meq/100g)	30	27	−10
Organic carbon (%)	28.55	34.55	21
Total nitrogen (%)	0.70	1.89	170
Carbon/nitrogen (C/N)	41	18	−56.1
Total phosphorus (mg/kg)	98.18	202.94	106.7
Ash content (%)	43	31	−27.9

Abbreviation: CEC, cation exchange capacity.

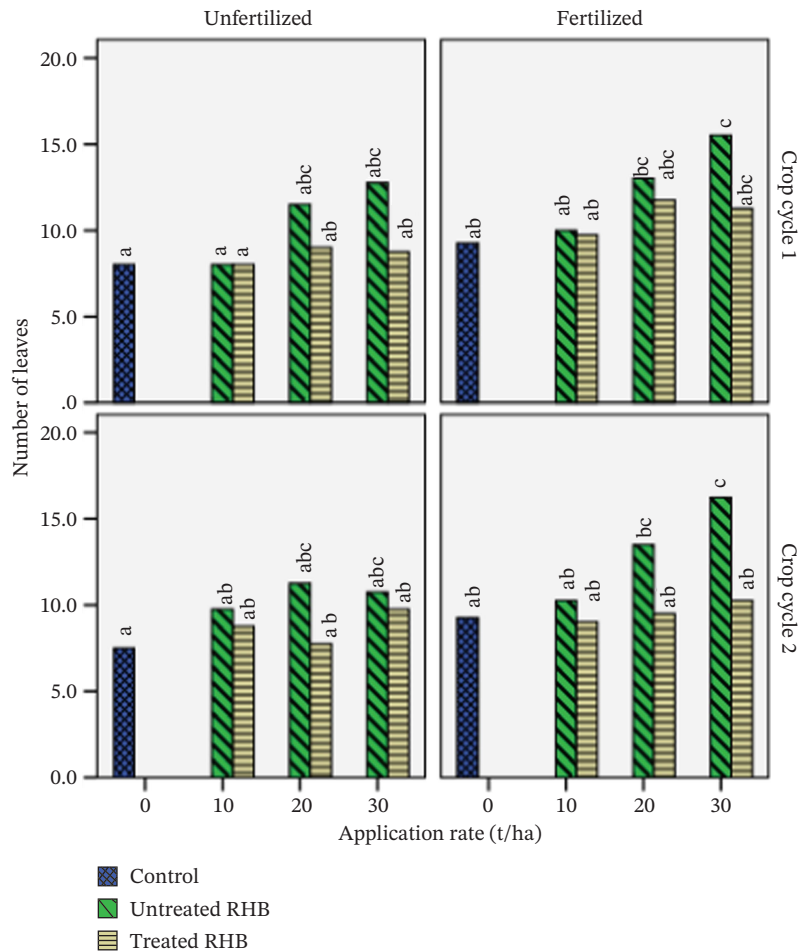


FIGURE 2 | Variation in the number of leaves of lettuce at harvest under different biochar treatments during crop cycles 1 and 2.

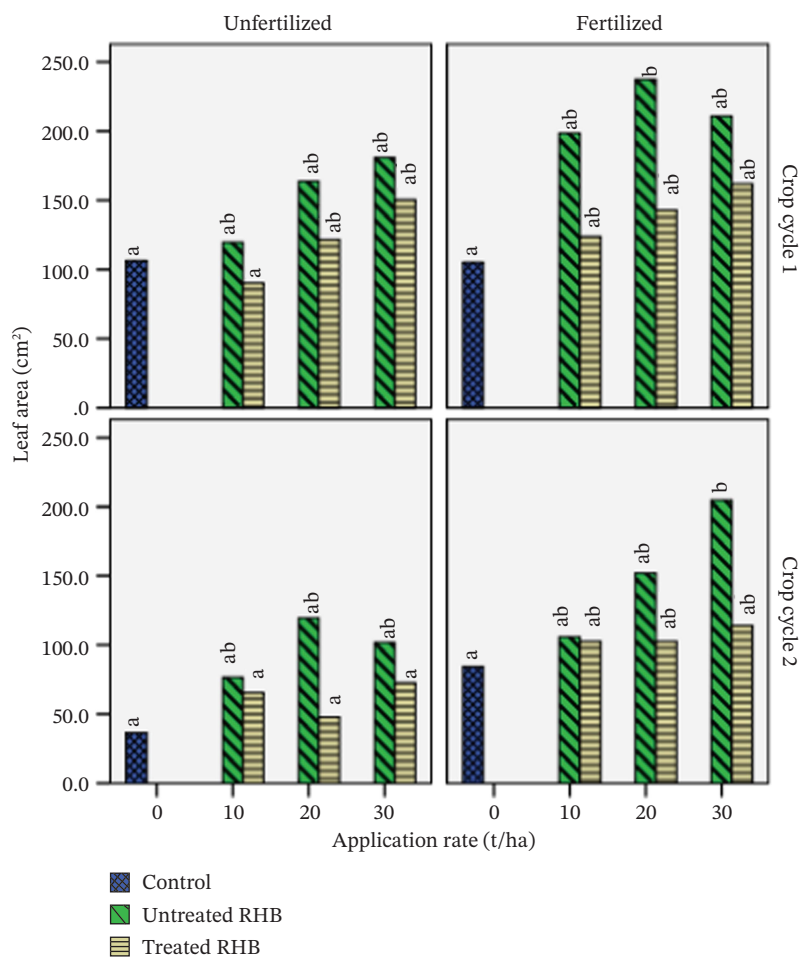


FIGURE 3 | Variation in leaf surface area of lettuce at harvest under different biochar treatments during crop cycles 1 and 2.

In the second crop cycle, RHB30 + F produced the tallest plants (23.4 cm), which was 100% taller than the fertilized control (11.7 cm). RHB plants were significantly taller ($p < 0.05$) than TRHB plants only at the 30 t/ha application rate. Overall, plants were taller in the first cropping cycle compared to the second. Figure 4 illustrates the variation in shoot height by treatment at harvest for both crop cycles.

3.2.4 | Effect on Aboveground Biomass Production

Aboveground biomass production increased with higher biochar application rates and fertilization (Figure 5). Significant differences ($p < 0.05$) in aboveground biomass production were observed among unfertilized treatments in both crop cycles. In the first crop cycle, RHB30 recorded the highest aboveground biomass (53.4 g), representing a 337.7% increase compared to the unfertilized control. TRHB30 achieved an 87.9% increase over the control, while TRHB10 produced 7.5% lower aboveground biomass than the control. No significant differences were observed between biochar treatments and the control at 10 t/ha and 20 t/ha application rates.

In the second crop cycle, RHB30 again produced the highest aboveground biomass (31.1 g), corresponding to a 436.4% increase relative to the unfertilized control. TRHB30 showed a substantial 244.1% increase. Fertilization significantly ($p < 0.05$) enhanced aboveground biomass production across all

treatments. The highest aboveground biomass was recorded in RHB30 + F, which was 296.5% higher than the fertilized control, followed by RHB20 + F (143.7% increase). The fertilized control performed better than TRHB10 and TRHB20 treatments. Other fertilized treatments were statistically similar to the fertilized control. Overall, pristine biochar treatments consistently outperformed TRHB treatments, particularly at the 30 t/ha rate. Figure 5 illustrates the variation in aboveground biomass production across treatments at harvest for both crop cycles.

4 | Discussion

Wastewater filtration did not result in an overall enrichment of the RHB. While increases occurred in bulk density (+45.1%), organic carbon (+21%), total nitrogen (+170%), and total phosphorus contents (+106.7%), substantial decreases were recorded in pH (from 8.5 to 6.0, -29.4%), ash content (-27.9%), cation exchange capacity (-10%), and several base cations (K: -49.8%, Ca: -22.2%, Mg: -13.6%, Na: -44.6%). The marked reduction in pH is most likely attributable to the loss of ash, which typically contributes to the liming capacity of alkaline biochars. Similar reductions in pH and ash content following wastewater exposure have been reported in other studies [6, 34]. The decrease in exchangeable base cations and CEC suggests leaching of these ions into the wastewater during the 6-month filtration period, especially under

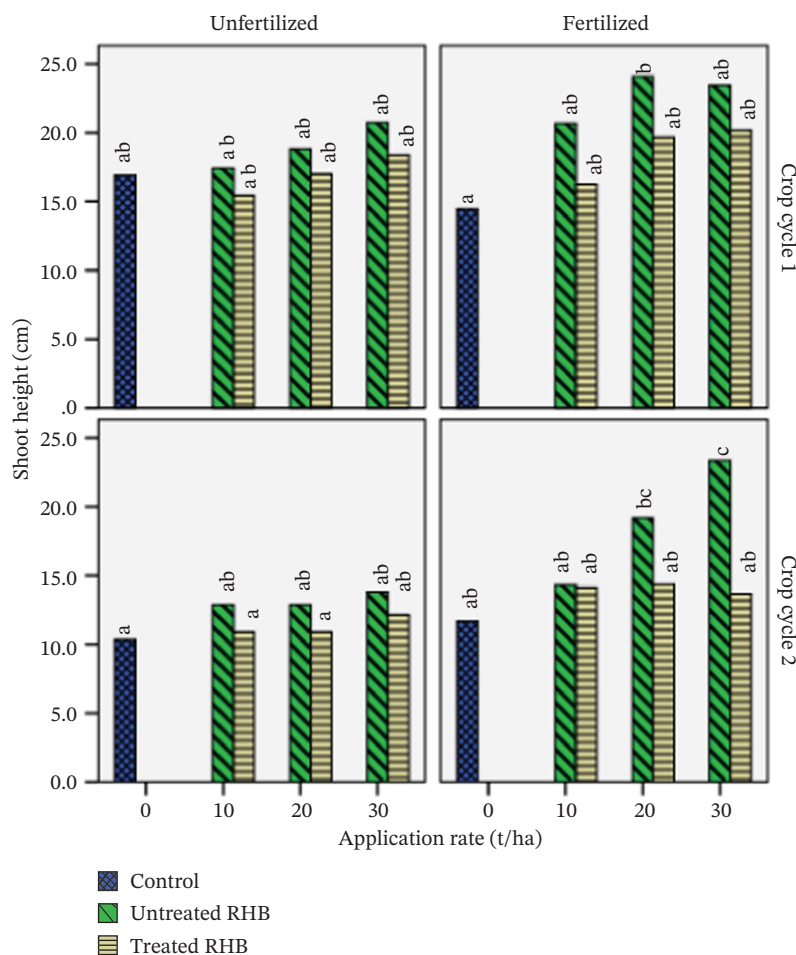


FIGURE 4 | Variation in shoot height of lettuce at harvest under different biochar treatments during crop cycles 1 and 2.

intermittent heavy rainfall conditions in the vertical flow system. The increase in bulk density and slight reduction in porosity (−4.4%) further suggest that pores were partially clogged by suspended solids and organic matter from the wastewater. Nonetheless, these biochars still possessed a lower bulk density compared to the soil used. Adding low bulk density biochar to compacted soils can enhance aeration, water infiltration, and root penetration [4, 34].

Conversely, the gains in organic carbon, nitrogen, and phosphorus indicate some retention and adsorption of organic matter and nutrients from the domestic wastewater. These observed increases in organic carbon and total nitrogen align with some previous findings. Sarkhot et al. [36] reported increases in carbon (9.3%) and nitrogen (8.3%) when wood shavings biochar was treated with dairy manure effluent for 24 h. Visiy et al. [33] also documented slight increases in organic carbon (1.1%) and nitrogen (0.77%) when corn cob biochar was used in domestic wastewater treatment over a 6-month period. However, the substantial increase in total phosphorus (+106.7%) in this study contrasts with Werner et al. [17] and Visiy et al. [33], who observed decreases in phosphorus content in wastewater-exposed rice husk and corn cob biochars, respectively. This discrepancy suggests that the direction and magnitude of nutrient changes during wastewater filtration depend on several factors, including biochar feedstock type, pyrolysis conditions, wastewater

characteristics, hydraulic loading rate, and duration of filtration. These variations highlight the need for further controlled experiments to elucidate the underlying mechanisms of nutrient retention and leaching when using biochar in dual-purpose applications.

In the pot trial, the effect of biochar application rate was clearly evident. Aboveground biomass production and other growth parameters generally increased with higher application rates, but significant ($p < 0.05$) improvements were mostly observed only at the highest rate of 30 t/ha. TRHB did not significantly improve lettuce growth and productivity compared to the unfertilized control at 10 and 20 t/ha, although modest aboveground biomass increases were recorded at 30 t/ha (87.9% and 244.1% in the first and second cycles, respectively). In contrast, pristine RHB consistently outperformed TRHB, with aboveground biomass increases reaching 337.7% and 436.4% at 30 t/ha in the first and second crop cycles, respectively. This rate-dependent response supports previous findings that a minimum application rate of around 30 t/ha is often required to observe tangible effects on lettuce growth [22, 34]. The superior performance of RHB over TRHB, particularly at higher rates, is likely due to its higher pH and greater content of base cations, which provided a stronger liming effect on the acidic oxisol (initial pH 5.5). The lower pH and reduced CEC of TRHB limited its ability to alleviate soil acidity and retain nutrients, thereby reducing plant-available nutrient supply.

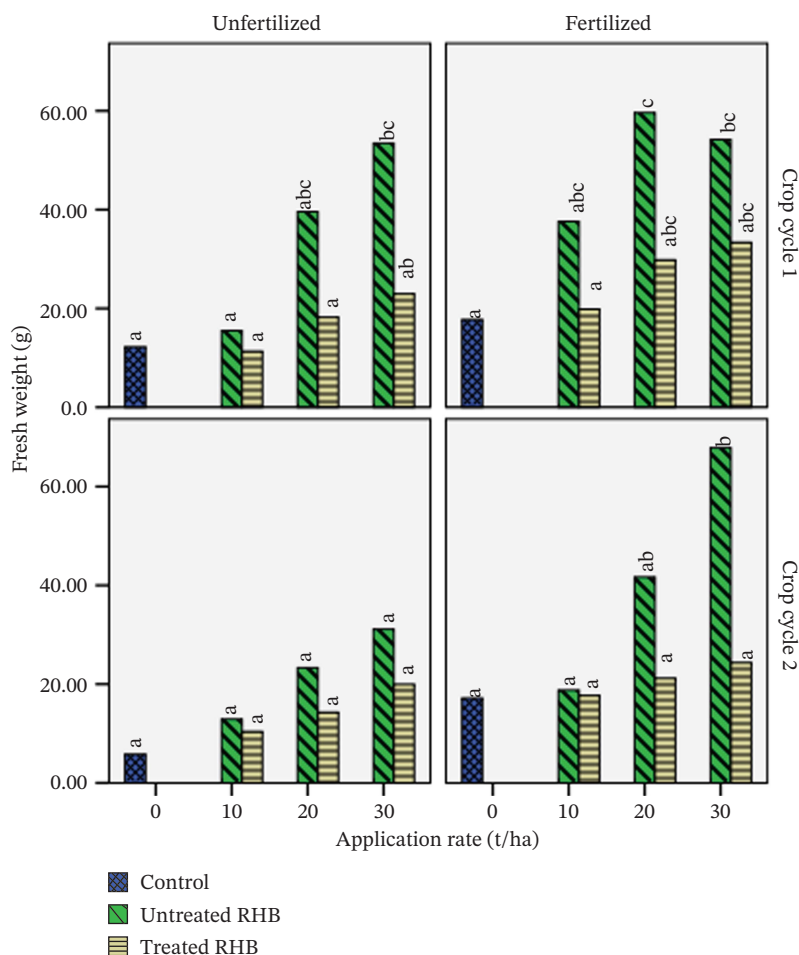


FIGURE 5 | Variation in lettuce aboveground biomass (fresh weight) across different biochar treatments at harvest during crop cycles 1 and 2.

These findings are consistent with previous studies on wastewater-treated biochars. Werner et al. [17] observed a 72% increase in spring wheat biomass with pristine RHB and only a 37% increase with the treated version. Similarly, Visiy et al. [33] reported a 322% increase in lettuce aboveground biomass with pristine corn cob biochar compared to 142% with the treated version. Oh et al. [37] noted lower lettuce yields when using biochar impregnated with anaerobically digested slurry compared to commercial fertilizer. Carter et al. [38] demonstrated that biochar application significantly influenced lettuce growth, with clear benefits observed at 30 t/ha. Upadhyay et al. [22] also found that 30 t/ha of green waste biochar was most effective for optimal lettuce growth in sand culture, though growth declined with higher rates due to increased pH and electrical conductivity. Similarly, Artiola et al. [34] reported higher lettuce yields at 40 t/ha compared to 80 t/ha, confirming the assertion that while increases in biochar application may increase plant growth, there exists a threshold beyond which plant growth will decline.

While biochar addition to soil produced better plant growth, a combination of fertilizer and biochar significantly improved yields, consistent with the findings of other researchers [34, 38]. In addition, the fertilized control outperformed the enriched biochar treatments at 10 t/ha and 20 t/ha. Kizito et al. [6] also obtained slightly lower yields (20%–25%) in digestate-enriched biochar compared to fertilized treatments. The slightly lower yield achieved from digestate-enriched biochar was attributed to

slower mineralization and release of the adsorbed nutrients in the short term. This confirms that biochar, particularly the treated form, cannot fully replace mineral fertilizers in the short term on nutrient-poor acidic soils. The relatively better performance of TRHB in the second crop cycle compared to the first suggests a possible slow-release effect or gradual improvement in soil conditions over time [34]. Overall, this study demonstrates both the opportunities and limitations of using RHB for dual purposes. While some nutrient enrichment (especially N and P) occurred during wastewater filtration, the substantial loss of ash and base cations reduced the liming capacity and overall agroeconomic value of TRHB compared to pristine RHB.

5 | Conclusions

The study tested the hypothesis that RHB used as a filter medium in domestic wastewater treatment can become sufficiently nutrient-enriched to serve as an effective soil amendment. The results showed that wastewater filtration led to partial nutrient enrichment, with notable increases in organic carbon (+21%), total nitrogen (+170%), and total phosphorus (+106%). However, these gains were accompanied by significant reductions in pH (−29.4%), ash content (−27.9%), cation exchange capacity (−10%), and base cations. In the pot trial, the TRHB produced modest increases in lettuce aboveground biomass compared to the unfertilized control, particularly at the 30 t/ha application

rate. Nevertheless, it consistently underperformed the pristine RHB, which showed substantially higher aboveground biomass increases. Significant improvements in plant growth were mainly observed at the highest application rate of 30 t/ha and when biochar was combined with mineral fertilizer.

These findings indicate that while wastewater filtration can enrich biochar with some nutrients, the loss of ash and base cations during prolonged filtration reduces its liming capacity and overall agronomic effectiveness on acidic tropical soils. The study demonstrates both the potential and the current limitations of the dual-use approach for RHB in wastewater treatment and soil amendment. Although TRHB showed some benefits over the control, it could not match the performance of pristine biochar in the short term. Long-term field studies are recommended to evaluate the residual effects of treated biochar and to explore strategies, such as shorter filtration periods, post-treatment reactivation, or co-application with lime or fertilizers to optimize its value.

Acknowledgments

The authors are grateful for the funding provided by the Pan-African University, Life and Earth Sciences Institute (including Health and Agriculture), University of Ibadan, Nigeria, and for the conducive research environment offered by the University of Dschang, Cameroon.

Funding

The study was funded by the Institute for Pan African University, Life and Earth Sciences Institute (Including Health and Agriculture), Ibadan, Nigeria.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data supporting the findings of this research are presented in the tables, figures, and explanations throughout the article. Additional datasets are available upon reasonable request from the corresponding author.

References

1. EBC/IBI, "Comparison of European Biochar Certificate Version 4. 8 and IBI Biochar Standards Version 2. 0 European Biochar Certificate First Publication March 2012," (2014), <http://www.european-biochar.org/en/homeIBIBiocharStandardsfirstpublicationhttp://www>.
2. L. F. Perez-Mercado, C. Lalander, C. Berger, and S. S. Dalahmeh, "Potential of Biochar Filters for Onsite Wastewater Treatment: Effects of Biochar Type, Physical Properties and Operating Conditions," *Water* 10, no. 12 (2018): 1–18, <https://doi.org/10.3390/w10121835>.
3. S. Sahar, *Dalahmeh, Capacity of Biochar Filters for Wastewater Treatment in Onsite Systems* (2016).
4. S. F. Billa, T. Evaristus, A. Ajebesone, and F. Ngome, "Agro—Environmental Characterization of Biochar Issued From Crop Wastes in the Humid Forest Zone of Cameroon," *International Journal of Recycling of Organic Waste in Agriculture* 8, no. 1 (2019): 1–13.
5. K. B. M. Djousse, S. E. Allaire, and A. D. Munson, "Quantifying the Influence of Eucalyptus Bark and Corn cob Biochars on the Physico-Chemical Properties of a Tropical Oxisol Under Two Soil Tillage Modes," *International Journal of Recycling of Organic Waste in Agriculture* 8, no. 9 (2019): 211–224.
6. S. Kizito, H. Luo, J. Lu, H. Bah, R. Dong, and S. Wu, "Role of Nutrient-Enriched Biochar as a Soil Amendment During Maize Growth: Exploring

- Practical Alternatives to Recycle Agricultural Residuals and to Reduce Chemical Fertilizer Demand," *Sustainability* 11 (2019): 1–22, <https://doi.org/10.3390/su11113211>.
7. E. B. Visiy, B. M. K. Djousse, L. Martin, et al., "Effectiveness of Biochar Filters Vegetated With *Echinochloa pyramidalis* in Domestic Wastewater Treatment," *Water Science and Technology* 85, no. 9 (2022): 2613–2624, <https://doi.org/10.2166/wst.2022.147>.
 8. B. M. K. Djousse, N. C. F. Djiokeng, M. Lekeufack, E. B. Visiy, S. M. Tsague, and M. R. G. Lontsi, "Potentiel des Biochars à Base de Résidus Agricoles Pour le Traitement des Eaux Usées Domestiques par Filtres à Flux Verticaux Plantés d'*Echinochloa Pyramidalis*," *Environnement, Ing. Dev.* 88 (2023): 33–42.
 9. H. Asadi, M. Ghorbani, M. Rezaei-Rashti, et al., "Application of Rice Husk Biochar for Achieving Sustainable Agriculture and Environment," *Rice Science* 28, no. 04 (2021): 325–343, <https://doi.org/10.1016/j.rsci.2021.05.004>.
 10. O. C. N. Ndoung, C. Celio de Figueiredo, and M. L. G. Ramos, "Heliyon Review Article A Scoping Review on Biochar-Based Fertilizers: Enrichment Techniques and Agro-Environmental Application," *Heliyon* 7, no. September (2021): 1–17, <https://doi.org/10.1016/j.heliyon.2021.e08473>.
 11. A. Pokharel, A. Bishnu, and A. Farooque, "Biochar—Assisted Wastewater Treatment and Waste Valorization," in *Applications of Biochar for Environmental Safety* (Berlin, Germany: Springer, 2020), 19, <https://doi.org/10.5772/intechopen.92288>.
 12. D. M. Olszyk, T. Shiroyama, J. M. Novak, et al., "Biochar Affects Essential Nutrients of Carrot Taproots and Lettuce Leaves," *HortScience* 55, no. 2 (2020): 261–271, <https://doi.org/10.21273/HORTSCI14421-19>.
 13. A. Sangodoyin and A. A. Amori, "Aerobic Composting of Cassava Peels Using Cowdung, Sewage Sludge and Poultry Manure as Supplements," *European International Journal of Science and Technology* 2, no. 8 (2013): 22–34.
 14. H. A. M. Hashfi, S. Syafrudin, and S. Suherman, "Rice Husk Waste: Impact on Environmental Health and Potential as Biogas," *Social, Endeavour for Health and Telemedicine* 18, no. 3 (2023): 431–436.
 15. N. Shukla, D. Sahoo, and N. Remya, "Biochar From Microwave Pyrolysis of Rice Husk for Tertiary Wastewater Treatment and Soil Nourishment," *Journal of Cleaner Production* 235 (2019): 1073–1079, <https://doi.org/10.1016/j.jclepro.2019.07.042>.
 16. B. Marschner, S. Werner, K. Alfes, and M. Lübken, "Potential Dual Use of Biochar for Wastewater Treatment and Soil Amelioration," *Geophysical Research Abstracts* 15, no. 1 (2013): 11260.
 17. S. Werner, K. Korbinian, M. Wichern, A. Buerkert, C. Steiner, and B. Marschner, "Agronomic Benefits of Biochar as a Soil Amendment After Its Use as Waste Water Filtration Medium," *Environment and Pollution* 233 (2018): 561–568.
 18. T. Edwin, M. Mera, P. S. Komala, and Z. Zulkarnaini, "Zulkarnaini, Impact of Pyrolysis Temperature on the Removal of Nutrients Using Coarse Rice-Husk Biochar," *Journal of Ecological Engineering* 24, no. 12 (2023): 247–257, <https://doi.org/10.12911/22998993/173379>.
 19. R. Williams, J. B. Belo, J. Lidia, et al., "Productivity Gains in Vegetables From Rice Husk Biochar Application in Nutrient—Poor Soils in Timor—Leste," *Scientific Reports* 13 (2023): 1–13, <https://doi.org/10.1038/s41598-023-38072-2>.
 20. B. S. Fru, T. E. Angwafo, T. N. Martin, N. Ajebesone, and T. P. Ngome, "Environmental and Socio-Economic Feasibility of Biochar Application for Cassava Production in the Bimodal Rainforest Zone of Cameroon," *International Journal of Rural Development, Environment and Health Research* 2, no. 1 (2018): 1–9, <https://doi.org/10.22161/ijreh.2.1.1>.
 21. D. Singh, et al., "An Overview on the Preparation of Rice Husk Biochar, Factors Affecting Its Properties, and Its Agriculture Application," *Journal of the Saudi Society of Agricultural Sciences* 21, no. 3 (2022): 149–159, <https://doi.org/10.1016/j.jssas.2021.07.005>.

22. K. P. Upadhyay, D. George, R. S. Swift, and V. Galea, "The Influence of Biochar on Growth of Lettuce and Potato," *Journal of Integrative Agriculture* 13, no. 3 (2014): 541–546, [https://doi.org/10.1016/s2095-3119\(13\)60710-8](https://doi.org/10.1016/s2095-3119(13)60710-8).
23. E. K. Akoto-Danso, et al., "Agronomic Effects of Biochar and Wastewater Irrigation in Urban Crop Agronomic Effects of Biochar and Wastewater Irrigation in Urban Crop Production of Tamale, Northern Ghana," *Nutrient Cycling in Agroecosystems* 2, no. 6 (2018): 1–17.
24. W. T. Tsai, S. C. Liu, H. R. Chen, Y. M. Chang, and Y. L. Tsai, "Textural and Chemical Properties of Swine-Manure-Derived Biochar Pertinent to Its Potential Use as a Soil Amendment," *Chemosphere* 89, no. 2 (2012): 198–203, <https://doi.org/10.1016/j.chemosphere.2012.05.085>.
25. R. Subedi, N. Taupe, I. Ikoyi, et al., "Chemically and Biologically-Mediated Fertilizing Value of Manure Derived Biochar," *Science of the Total Environment* 550 (2016): 924–933, <https://doi.org/10.1016/j.scitotenv.2016.01.160>.
26. N. Kannari, T. Uesugi, K. Kubota, et al., "Calcium-Enriched Biochar: Pyrolysis of Digested Sludge, Phosphorus Recovery, and Fertilizer Properties," *Journal of the Japan Institute of Energy* 99, no. 12 (2020): 236–242, <https://doi.org/10.3775/jie.99.236>.
27. J. S. S. Carneiro, I. C. A. Ribeiro, B. O. Nardis, C. F. Barbosa, J. F. Lustosa Filho, and L. C. A. Melo, "Long-Term Effect of Biochar-Based Fertilizers Application in Tropical Soil: Agronomic Efficiency and Phosphorus Availability," *Science of the Total Environment* 760 (2021): 143955, <https://doi.org/10.1016/j.scitotenv.2020.143955>.
28. J. Chew, L. Zhu, S. Nielsen, et al., "Biochar Based Fertilizer: Supercharging Root Membrane Potential and Biomass Yield of Rice," *Science of the Total Environment* 713 (2020): 136431, <https://doi.org/10.1016/j.scitotenv.2019.136431>.
29. A. A. Karim, M. Kumar, S. Mohapatra, S. K. Singh, and C. R. Panda, "Co-plasma Processing of Banana Peduncle With Phosphogypsum Waste for Production of Lesser Toxic Potassium–Sulfur Rich Biochar," *Journal of Material Cycles and Waste Management* 21, no. 1 (2019): 107–115, <https://doi.org/10.1007/s10163-018-0769-7>.
30. W. Shi, Y. Ju, R. Bian, et al., "Biochar Bound Urea Boosts Plant Growth and Reduces Nitrogen Leaching," *Science of the Total Environment* 701 (2020): 134424, <https://doi.org/10.1016/j.scitotenv.2019.134424>.
31. H. Zhang, R. P. Voroney, G. W. Price, and A. J. White, "Sulfur-Enriched Biochar as a Potential Soil Amendment and Fertilizer," *Soil Research* 55, no. 1 (2017): 93–99, <https://doi.org/10.1071/sr15256>.
32. S. Sharma, S. Mukherjee, S. Bolan, et al., "Biochar as a Potential Nutrient Carrier for Agricultural Applications," *Current Pollution Reports* 11, no. 19 (2025): 1–36, <https://doi.org/10.1007/s40726-025-00349-7>.
33. E. B. Visiy, B. M. K. Djousse, A. Sangodoyin, A. S. Gbadegesin, and T. Fonkou, "Impact of the Application of Biochar Previously Used in Domestic Wastewater Treatment on the Growth of Lettuce (*Lactuca sativa*)," *Journal of Applied and Natural Science* 14, no. 3 (2022): 963–970, <https://doi.org/10.31018/jans.v14i3.3731>.
34. J. F. Artiola, C. Rasmussen, and R. Freitas, "Effects of a Biochar-Amended Alkaline Soil on the Growth of Romaine Lettuce and Bermudagrass," *Soil Science* 177, no. 9 (2012): 561–570, <https://doi.org/10.1097/ss.0b013e31826ba908>.
35. J. Pauwels, E. Van Ranst, M. Verloo, and A. M. Ze, "Manuel de Laboratoire de Pédologie," *Méthodes D'Analyses de Sols et de Plantes; Équipement et Gestion des Stocks de Verrerie et de Produits Chimiques*, 28 (Bruxelles, Belgique: A. G. C. D. Publications Agricoles n°, 1992).
36. D. V. Sarkhot, A. A. Berhe, and T. A. Ghezzehei, "Impact of Biochar Enriched With Dairy Manure Effluent on Carbon and Nitrogen Dynamics," *Journal of Environmental Quality* 41, no. July (2012): 1107–1114, <https://doi.org/10.2134/jeq2011.0123>.
37. T.-K. Oh, Y. Shinogi, S.-J. Lee, and B. Chol, "Utilization of Biochar Impregnated With Anaerobically Digested Slurry as Slow-Release Fertilizer," *Journal of Plant Nutrition and Soil Science* 177, no. 1 (2014): 97–103, <https://doi.org/10.1002/jpln.201200487>.
38. S. Carter, S. Shackley, S. Sohi, T. B. Suy, and S. Haefele, "The Impact of Biochar Application on Soil Properties and Plant Growth of Pot Grown Lettuce (*Lactuca sativa*) and Cabbage (*Brassica chinensis*)," *Agronomy* 03, no. 2 (2013): 404–418, <https://doi.org/10.3390/agronomy3020404>.