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Lactuca sativa Growth and Yield as Affected by Cashew Nut Shells Biochar, Cattle Manure and Urea in Northern and Central Benin

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Authors' contributions

This work was carried out in collaboration among all authors. Author ELS designed the study, performed the statistical analysis, wrote and prepared the original draft of the manuscript. Authors MA and ARGN collected the data and did analysis of the study. Authors NDBB and OJA managed the literature searches and revised the manuscript. Author GLA supervised the study. All authors read and approved the final manuscript.

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ABSTRACT

Aims: This study aims to identify good combinations of cashew nut shell biochar, cattle manure, and urea for enhancing lettuce (*Lactuca sativa* L.) growth and yield in the North and Central regions of Benin.
Place and Duration of Study: Two agronomic trials were conducted: one in Tchaourou, Borgou department (2022), and another in Dassa, Colline department (2023).
Methodology: A Fisher experimental design with three replications was used at each site, focusing on fertilization with seven treatments, including four reference treatments (local practices) and three treatments based on the reference treatments with biochar incorporation.
Results: The results demonstrated significant improvements in plant growth parameters and yield, with the application of biochar combined with cattle manure and urea or with cattle manure only. The plants leaves number, height and yields obtained from the application of 10 t ha^{-1} biochar + 20 t ha^{-1} cattle manure and 10 t ha^{-1} biochar + 0.025 t ha^{-1} urea +10 t ha^{-1} cattle manure were respectively at least 165 and 318%; 25 and 50%; 42 and 91% higher than those obtained under the producer's mineral fertilization practice at both sites.
Conclusion: The findings showed that integrating cashew nut shell biochar with organic and inorganic fertilizers can significantly enhanced lettuce production, and thus overall vegetable crop yields while reducing the need for mineral fertilizers and dependence of cattle manure. Additionally, studying the best application methods and rates for different soil types and crop systems can help in maximizing the benefits of biochar.

Keywords: Cashew nut shell biochar; cattle manure; urea; lettuce; fertilization; vegetable crops.

1. INTRODUCTION

In sub-Saharan Africa, fruit and vegetable production has become a crucial agricultural sector due to their nutritional value and the significant economic income they generate [1,2]. This sector has the potential to drive agricultural and economic diversification, particularly for smallholders who can target local, regional, or export markets [3,4]. Indeed, fruits and vegetables are essential sources of nutrients and micronutrients (potassium, calcium, iron, iodine, vitamin A, and zinc) necessary for healthy diet and good health [5]. Intensified vegetable production generates more income and employment than other segments of the agricultural economy [5]. According to Joosten et al. [6], the profits per hectare are 3 to 14 times higher in vegetable production compared to rice production. Vegetable production also creates more jobs per hectare than cereals [4]. In Benin, market gardening is a nationwide activity because it is essential for the population's nutritional balance and the improvement of agricultural producers' incomes [7,8]. Vegetable production is common in various ecologies, notably on plateaus, alluvial plains, valleys, lowlands, and along the coast [9].

Among the primary leafy vegetables cultivated is lettuce (*Lactuca sativa*) [10], which is widely consumed. According to the World Health Organization (WHO), the recommended vegetable intake per capita per day is 400 grams [11]. However, in Benin, vegetable consumption per adult is around 99.1 grams per day [12]. To meet this increasing demand of vegetable, producers are resorting to intensive mineral fertilization [13]. Excessive use of chemical fertilizers exacerbates soil acidity and depletes organic matter, leading to reduced soil fertility and yields [14]. Therefore, appropriate fertilization management measures are necessary to restore and maintain soil fertility and ecological balance [15]. One promising solution is the use of organic fertilization. Various studies have reported that organic fertilizers are a good substitute for chemical fertilizers, improving soil fertility and plant development [16,17,18].

Given the challenges of excessive mineral fertilization, exploring local organic resources like cashew nut shells offers a promising alternative. In Benin, particularly in the North and Center, local organic resources are available in addition to animal waste (cattle manure, poultry droppings). Cashew nuts (*Anacardium occidentale*), the second-largest export product after cotton [19], generate substantial quantities of residues. This crop involves more than 200,000 actors who engage in production, processing, and marketing within different value chains [19]. With the increasing number of factories, there is an abundant production of shells (10,959 tonnes in 2013), which are challenging for processing units to manage [20]. To create added value, some processing units recycle cashew nut shells by extracting cashew nut shell liquid [21]. Additionally, the shells are stored in processing plants and used directly as fuel. Pyrolyzers convert cashew shells into gas and charcoal [20]. Studies by Godjo et al. [20] showed that the pyrolysis reactor could recover approximately 82% of the mass of treated shells as gas and produce about 18% as charcoal. However, they contain approximately 16% carbon, 3% to 7% ash, and 4% nitrogenous materials [22].

Biochar, derived from the pyrolysis of organic waste under controlled conditions, has received increased global attention as an amendment to maintain a high stock of organic matter [23]. It gradually mineralizes in the soil because it contains a high recalcitrant C content in humid tropical soils [24]. Recalcitrant C pools are the fractions of C that take longer to decompose and are not readily available to microorganisms [25,26]. In addition to improving soil productivity and quality, the recalcitrant C pool contributes to the total organic carbon (TOC) stock [27,28]. Biochar significantly contributes to cation retention [29] and improves soil fertility by directly adding nutrients [23,30]. Thus, it offers better nutrient availability to plants, positively impacting their growth and development [31,32,33]. However, it needs to be combined with mineral or organic fertilizers to ensure satisfactory crop productivity [34,35,36]. Maccarthy et al. [35] showed that economic returns (Gross Margin, Gross Yield, and Benefit-Cost Ratio) improved when biochar was combined with inorganic fertilizers. Despite this potential, the adoption of biochar and organic/inorganic fertilization methods remains low among local farmers, as producers often prefer simpler methods [37].

The main reason for this low adoption is the limited research focused on the valorization of cashew nut shells in soil fertilization or evaluating the potential of biochar in real-world crop fertilization. The central research question is: How does the incorporation of biochar derived from cashew nut shells, alone or in combination with cattle manure and/or urea, affect the growth performance and yield of lettuce (*Lactuca sativa* L.) in the diverse agroecological zones of North and Central Benin?

The objective of this study was to evaluate the individual and combined effects of cashew nut shell biochar, cattle manure, and urea on lettuce growth and yield in North and Central Benin. We hypothesize that cashew nut shell biochar, integrated with or without organic fertilizers, can enhance productivity and improve soil fertility in market gardening, particularly lettuce cultivation, in North and Central Benin.

2. MATERIALS AND METHODS

2.1 Study Area

This study was conducted in two agroecological zones in Benin. The field trials were conducted during the same period in the municipality of Tchaourou (Borgou department) in North Benin during 2022 (Site 1) and in the municipality of Dassa (Colline department) in Central Benin during 2023 (Site 2). The site 1 experiences a South Sudanian climate characterized by one rainy season and one dry season, with annual rainfall averaging between 1100 and 1200 millimeters and an average temperature of 26.8°C [38]. The main soil types in this area are weakly concretioned tropical ferruginous types. In contrast, Site 2 is under a Sudano-Guinean climate with two rainy seasons and two dry seasons, often with unpredictable weather patterns. The annual number of rainy days ranges between 80 and 110, with annual rainfall averaging 907 millimeters and an average temperature of 29°C. The soils in this region are tropical ferruginous on a crystalline base, exhibiting highly variable characteristics [39]. The soil characteristics of the two sites are presented on Table 1. On both sites, the soils have a sandy-loamy texture, moderate content of P and very low content of potassium. They presented respectively neutral and moderately acid pH, very low and low nitrogen content, moderate and low carbon content, with rapid and slow decomposition of organic matter according to C/N ratio. The sandy-loamy texture and low potassium content of soil at both sites as well as moderately acid pH and low carbon content on site 2 could affect soil nutrient availability and consequently, the growth response of lettuce to different fertilization treatments, notably in absence of organic matter adding. The low nitrogen content indicates need of nitrogen fertilizer application for good growth of leafy vegetable [40].

Table 1. Soil characteristics on site 1 and 2 (North and central Benin)

Soil characteristics	Texture	pH	Carbon (%)	Nitrogen (%)	Ratio carbon: nitrogen	Phosphorus mg/kg	Potassium (meq/100g)
Site 1	Sandy-loam	6.89	1.14	0.035	32.57	15.45	0.59
Site 2	Sandy-loam	5.80	0.81	0.05	15.89	12.00	0.35

2.2 Plant Material and Organic Substrate Used

The plant material used in this study consisted of "EDEN" variety seed, which is adapted to the local climate and is the common variety cultivated by farmers in the two areas. This variety has a cycle length of approximately 51 days. The organic amendments used in this study were selected for their potential to enhance soil fertility and crop productivity. This included biochar derived from cashew nut shells, cattle manure, and the mineral fertilizer urea, which contains 46% nitrogen (see Table 2 for details).

At the start and end of the experiment, representative composite samples were taken from the top 20 cm of soil in each replication. The laboratory analyses performed included:

- pH (water): measured by the potentiometric method (Jackson, 2005) [41];
- Total nitrogen: determined by the Kjeldahl method (Fleck, 1967) [42];
- Assimilable phosphorus: measured by the Bray I method (Bray and Kurtz, 1945) [43]
- Exchangeable potassium: assessed by method of Helmke and Sparks (1996) [44]
- Organic matter: determined by incineration method (Bell, 1964) [45].

2.3 Experimental Design and Management

The experimental design on each site was a Fisher design focusing on fertilization as the factor with seven treatments (T0 = control, PPFO = producers practice of organic fertilization = 40 t ha^{-1} cattle manure, PPFM = producers practice of mineral fertilization = 0.1 t ha^{-1} urea, PPFOM = producers practice of organo-mineral fertilization = 20 t ha^{-1} cattle manure + 0.05 t ha^{-1} urea, Biochar + FM = 10 t ha^{-1} biochar + 50% of producers mineral fertilization rate = 10 t ha^{-1} biochar + 0.05 t ha^{-1} urea, Biochar + FO = 10 t ha^{-1} biochar + 50% of producers organic fertilization rate = 10 t ha^{-1} biochar + 20 t ha^{-1} cattle manure and Biochar + FM +FO = biochar + 25% of producers mineral fertilization rate + 25% of producers organic fertilization rate = 10 t ha^{-1} biochar + 0.025 t ha^{-1} urea +10 t ha^{-1} cattle manure) including four (4) reference treatments (producers practice) and three replications (blocks) (Table 3).

Each experimental unit had an area of 2.4 m² (2 m x 1.2 m). The distance between the experimental plots was 0.5 m, and the distance between two blocks was 1 m. The sowing lines were arranged along the lengths of the experimental units with a spacing of 20 cm between lines and 20 cm between plants.

After soil weeding, the nursery was installed and the elementary plots were demarcated. Cattle manure and biochar were applied as basal fertilizers two weeks before transplanting to allow for initial soil conditioning and nutrient integration (Table 3). For this purpose, they were weighed and applied as basal fertilizer two weeks before transplanting on the elementary plots, which were watered twice a day (morning and evening) for one week before transplanting. The mineral fertilizer was applied in two equal fractions as maintenance fertilizer, one and three weeks after transplanting. Transplanting was done after 21 days of nursery. The plants were then watered twice a day (morning and evening), using two 14-liter watering cans per plot. the Weeding and hoeing were carried out as needed. Phytosanitary treatment of the plants was carried out on the 15th and 30th day after transplanting; using neem oil, at a rate of 125 ml of neem oil diluted in 16 liters of water. Neem oil was selected for phytosanitary treatment due to its eco-friendly properties and effectiveness against common pests in the region.

2.4 Growth and Yield Parameters Measurements

The growth data collected during the trial were: the height of the plants measured from the collar to the apex using a graduated ruler; and the number of leaves emitted by counting all the

Table 2. Chemical characteristics of organic substrates used at sites 1 and 2

Site	Fertilizer	Carbon (%)	Nitrogen (%)	Ratio carbon:nitrogen	Phosphorus (mg/kg)	Potassium (meq/100 g)	pH
Site 1	Cattle manure	15.72	0.93	16.9	1.47	5.87	8.01
	Biochar from hulls	37.04	0.61	60.72	0.51	2.10	9.81
Site 2	Cattle manure	19.26	1.33	25.6	0.43	1.39	8.51
	Biochar from hulls	34.40	0.58	59.3	0.33	2.02	10.75

Table 3. Details of treatments included in the experimental design

Fertilizers	Reference treatments				Treatments including biochar using		
	T0	PPFM (t ha^{-1})	PPFO (t ha^{-1})	PPFOM (t ha^{-1})	Biochar + 50% PPFM (t ha^{-1})	Biochar + 50% PPFO (t ha^{-1})	Biochar + 25% PPFM + 25% PPFOM (t ha^{-1})
Urea	-	0.1	-	0.05	0.05	-	0.025
Cattle manure	-	-	40	20	-	20	10
Biochar	-	-	-	-	10	10	10

leaves emitted by the plant. These two data were collected from one week after transplanting and weekly on six (06) plants chosen at random from the useful surface area.

Harvest took place six weeks after transplanting by pulling up of plants on each elementary plot. these plants were washed with water to remove sand from the roots and leaves and then weighed using an electronic balance. To calculate the average weight of plants and yield of fresh biomass, the number of plants harvested from each elementary plot were counted. The average mass of harvested plants (P) per treatment was estimated by the following formula:

$$m \text{ (g/plant)} = M/N$$

Where M = total mass of plants harvested from a plot (g); N = number of plants harvested from an elementary plot.

The fresh biomass yield (R) was determined by the following formula: $R \text{ (t/ha)} = m*D*1000$

Where m = average mass of harvested plant (kg/plant) and D = lettuce density per hectare

2.5 Statistical Analysis

For Data analysis, the factors involved in experimentation were considered differently depending on their nature. Treatments (fertilization modalities) and Time were considered as fixed factors, and replication (Block) as a random factor. For growth data, a linear mixed-effect model was performed on plant height and a generalized linear mixed-effect model of the fish type was performed on number of leaves counted on each plant. This was done to assess the effect of treatments and time on plant height and number of leaves. For yield data, a linear mixed-effect model was performed to evaluate treatments effect. All Analyses were performed using R 4.3.3. statistical software.

3. RESULTS

3.1 Influence of Cashew Nut Shells Biochar, Cattle Manure and Urea on Lettuce Growth

The Table 4 shows the results of linear mixed model analysis on growth data. The treatments significantly influenced plant height at both sites over time ($p < 0.05$). Additionally, treatment and time had a distinctly significant effect on the number of leaves produced at both Site 1 and Site 2 (Table 4).

To this end, we noted an increase in leaves number over time until four weeks after transplanting (T4) on both sites. Indeed at site 1 and 2, the highest number of leaves were recorded under treatments Biochar + FO + FM (6 ± 2 and 9 ± 3.39 leaves respectively), PPFO (6 ± 2 and 10 ± 3.77), PPFOM (5 ± 2 and 9 ± 3.54), Biochar + FO (5 ± 2 and 9 ± 2.87) and Biochar + FM (5 ± 2 and 9 ± 2.91 leaves respectively), while the lowest number of leaves were recorded under PPFM (4 ± 2 and 6 ± 2.08) and control treatment (4 ± 2 and 7 ± 2.38) (Fig. 1).

Like leaves number, the plants height also increased significantly over time. Thus, at four months after transplanting (T4) we note at Site 1 a highest height under treatments PPFO (8.56 ± 0.54 cm), Biochar + FO + FM (8.34 ± 0.54 cm) and Biochar + FO (8.15 ± 0.54 cm); while at site 2, the highest height was observed under treatments PPFOM (19.75 ± 0.69 cm), PPFO (19.59 ± 0.69 cm), Biochar + FO + FM (19.12 ± 0.69 cm), followed by treatment Biochar + FO. (18.73 ± 0.69 cm) (Fig. 2).

3.2 Influence of Cashew Nut Shells Biochar, Cattle Manure and Urea on Lettuce Yield

The Table 5 presents the influence of treatments on lettuce yield. It shows that lettuce yield varied significantly depending on treatment ($p<0.05$). Thus, the best yields at the first site were obtained from plants having received the treatment PPFO (10.49 ± 4.62 t/ha), followed by Biochar + FO + FM (8.25 ± 4.41 t/ha). On site 2, the best yields are also obtained from plants having received the PPFO treatment (40.96 ± 11.59 t/ha) and Biochar + FO + FM (34.57 ± 5.94), followed by PPFOM (30.01 ± 8.73 t/ha) and Biochar + FO (27.15 ± 1.25 t/ha) treatments. The lowest yields were observed under the T0 and PPFM treatments at the two sites with respectively 2.27 ± 0.79 t/ha, 3.11 ± 1.83 t/ha on site 1 and 6.48 ± 3.84 t/ha, 3.78 ± 1.38 t/ha on site 2 (Table 5).

Table 4. Linear mixed model outputs on growth data

Treatments	Leaves number		Heigth (cm)	
	Site 1	**Site 2**	**Site 1**	**Site 2**
Biochar + FM	5 ± 2 [a]	9 ± 2.91 [a]	5.18 ± 2.03 [a]	11.66 ± 3.77 [b]
Biochar + FO	5 ± 2 [a]	9 ± 2.87 [a]	5.36 ± 2.28 [a]	13.65 ± 4.01 [a]
Biochar + FO + FM	6 ± 2 [a]	9 ± 3.39 [a]	5.90 ± 2.30 [a]	13.12 ± 5.04 [ab]
PPFM	4 ± 2 [b]	6 ± 2.08 [b]	4.13 ± 1.76 [b]	7.12 ± 2.30 [c]
PPFO	6 ± 2 [a]	10 ± 3.77 [a]	5.67 ± 2.26 [a]	14.51 ± 4.32 [a]
PPFOM	5 ± 2 [a]	9 ± 3.54 [a]	5.24 ±1.85 [a]	13.62 ± 4.73 [a]
T0	4 ± 2 [b]	7 ± 2.38 [b]	3.70 ± 1.92 [b]	7.25 ± 2.28 [c]
T1	3 ± 1 [c]	6 ± 1.08 [a]	3.45 ± 0.94 [d]	7.14 ± 1.94 [d]
T2	5 ± 4 [b]	7 ± 1.39 [b]	4.36 ± 1.34 [c]	10.33 ± 3.05 [c]
T3	5 ± 2 [b]	9 ± 1.93 [c]	5.41 ± 1.96 [b]	12.50 ± 3.95 [b]
T4	7 ± 3 [a]	12 ± 3.10 [d]	6.88 ± 2.49 [a]	16.27 ± 4.60 [a]
Source of variation	Pr>(F/Chisq)	Pr>(F/Chisq)	Pr>(F/Chisq)	Pr>(F/Chisq)
Treatment	< 2.2e-16 ***	< 2.2e-16 ***	0.001248 **	934e-08 ***
Time	6.726e-13***	< 2.2e-16 ***	< 2.2e-16 ***	7.811e-07 ***
Treatment:Time	0.4254	0.9999	0.010149 *	5.980e-07 ***
Block	-	-	0.15782	0.20398
Treatment:Block	-	-	0.03199 *	0.08876
Time:Block	-	-	1.00000	0.80839
Treatment:Time:Block	-	-	1.73e-09 ***	1.993e-06 ***

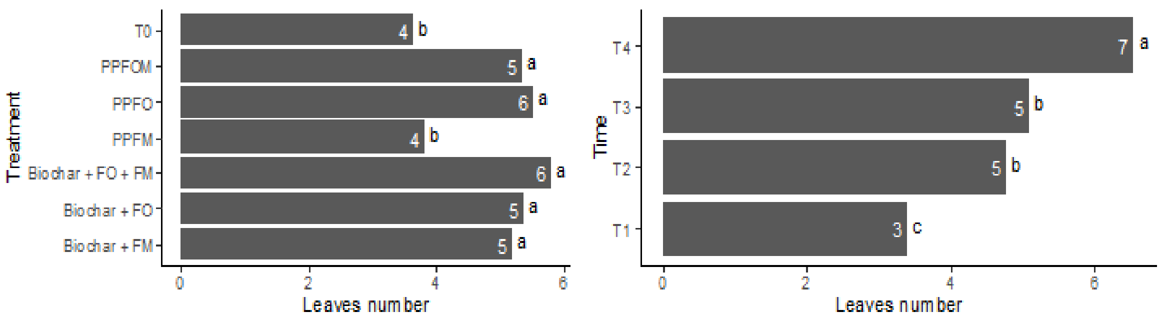

Fig. 1. Influence of treatments and time on leaves number

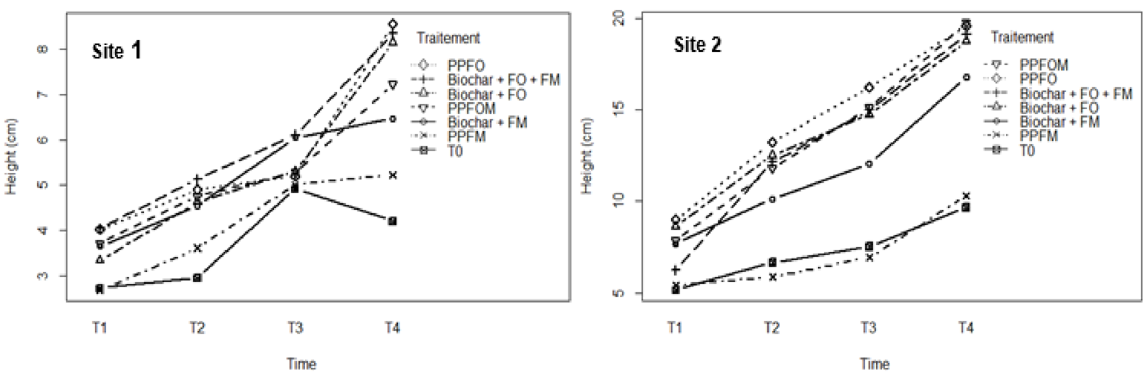

Fig. 2. Effect of treatment: Time on plants height

Table 5. Effect of treatments on lettuce yield

Treatments	Yield (t/ha)	
	Site 1	**Site 2**
Biochar + FM	6.52 ± 2.64 ab	16.25 ± 3.32 bc
Biochar + FO	6.72 ± 1.72 ab	27.15 ± 1.25 b
Biochar + FO + FM	8.25 ± 4.41 ab	34.57 ± 5.94 ab
PPFM	3.11 ± 1.83 b	6.48 ± 3.84 c
PPFO	10.49 ± 4.62 a	40.96 ± 11.59 a
PPFOM	6.80 ± 2.15 ab	30.01 ± 8.73 b
T0	2.27 ± 0.79 b	3.78 ± 1.38 c
Source of variation	Pr>(F/Chisq)	Pr>(F/Chisq)
Treatment	0.002912 **	2.22e-05 ***
1 | Block	0.09621	0.1896
1 | Treatment:Block	1.00000	1.00000

4. DISCUSSION

This study examined the impact of cashew nut shell biochar, cattle manure, and urea on the growth and yield of lettuce (*Lactuca sativa*) in North and Central Benin. The results demonstrate significant effects of fertilization modalities on lettuce growth and yield, highlighting the potential of organic and integrated fertilization strategies to enhance sustainable vegetable production.

4.1 Growth Parameters

The treatments significantly influenced key growth parameters such as number of leaves and plant height. The treatments: Biochar + FO (10 t ha^{-1} biochar + 20 t ha^{-1} cattle manure) and Biochar + FO + FM (10 t ha^{-1} biochar + 0.025 t ha^{-1} urea +10 t ha^{-1} cattle manure) consistently yielded the highest growth metrics across both sites, indicating that biochar, when combined with organic fertilizers, or both organic and mineral fertilizers can significantly boost lettuce growth. These results can be explained by the fact that biochar improved soil nutrient availability, especially that of nitrogen [32,46]. Indeed, Biochar significantly contributes to cation retention and improves soil fertility by directly adding nutrients [47]. Biochar increases the availability of C, N, Ca, Mg, K, and P for plants, as it absorbs and slowly releases nutrients [48,49,50]. Biochar improves nutrient fixation and release rates, thereby enhancing soil nutrient use efficiency [48,49]. Balanced fertilization improves agronomic variables such as plant height, number of leaves, stem diameter, and stem length [51]. Nutrient enrichment of biochar allows the penetration of available nutrients into the micro and nanopores of the biochar and they are released slowly according to the synchrony between nutrient supply and plant demand [52,53]. The slow-release mechanism based on crop physiological needs increases nitrogen use efficiency (NUE), reduces leaching losses and increases nutrient bioavailability, resulting in increased crop productivity [54,55,56,57,58]. Nitrogen stimulates the production of green leaves, thereby increasing the photosynthetic surface area [59]. Phosphorus supports proper root development, which enhances the absorption of other nutrients and the anchoring of the plant [60,61,62]. The application of potassium (K) can significantly improve the quality of lettuce at maturity [51,63]. Studies suggest that the lack of nitrogen (N) and phosphorus (P) significantly reduces lettuce biomass at the young leaf stage [64]. Carter et al. [65] noted an increase in the above-ground biomass of lettuce (*Lactuca sativa*) and Chinese cabbage (*Brassica chinensis*) after biochar application. This is consistent with the studies by Nabavinia et al. [66] and Jabborova et al. [67], which reported that biochar application increased root growth and morphological parameters. Moreover, manure stimulates soil microbial activity and further promotes nutrient release and transformation [68]. Liang et al. [15] observed in their study, an improvement in soil nutrient use efficiency and a more favorable soil environment for rice growth by the combined application of biochar and manure. Our results corroborate those of Sarmento et al. [69], who also obtained a significant increase in growth parameters on the lettuce, by combining application of biochar and goat manure. This finding also aligns with finding of Glaser et al. [30] and Agegnehu et al. [34], who have reported improved plant growth due to the enhanced nutrient availability and soil structure associated with biochar amendments.

4.2 Yield

Lettuce yield varied significantly depending on treatments, with the PPFO (40 t ha^{-1} cattle manure) and Biochar + FO + FM (10 t ha^{-1} biochar + 0.025 t ha^{-1} urea +10 t ha^{-1} cattle manure) treatments (followed by PPFOM: 20 t ha^{-1} cattle manure + 0.05 t ha^{-1} urea and Biochar + FO: 10 t ha^{-1} biochar + 20 t ha^{-1} cattle manure) producing the highest yields. These findings suggest that the integration of biochar with organic and mineral fertilizers can substantially enhance crop production. The superior yields from these treatments can be attributed to the synergistic effects of improved soil fertility, increased nutrient retention, and better water holding capacity provided by the biochar [23,29]. Indeed, biochar mixed with minerals or organic amendments provides more available nutrients in the soil and increases nutrient absorption by plants [15,52,55]. Raj et al. [70] observed an increase in the availability of soil nutrients (total N, P, and K) after applying biochar combined with bovine urine. Pandit et al. [71] also showed an increase in available P up to 105 mg kg^{-1} after applying nutrient-enriched biochar (co-composted biochar) compared to non-enriched biochar (38 mg kg^{-1}). Several studies have reported significant positive effects of available P and K in the soil on crop productivity [55,72,73,74,75]. Our findings are consistent with those of Raj et al. [70], who demonstrated that biochar enriched with bovine urine increases corn yield, unlike biochar added separately, even when both received the same amount of organic and inorganic supplements. Similarly, Schmidt et al. [53] observed that biochar mixed with cow urine led to a pumpkin yield of 82.6 t·ha^{-1}, an increase of over 300% compared to the treatment where only urine was applied, and an 85% increase compared to the treatment with biochar alone. Similar observations were noted by Sarmento et al. [69], who evaluated the application of goat manure and biochar on lettuce yield in Brazil; and Lele et al. [76], who assessed the effect of mineral fertilizer combined with biochar on corn and cassava yield. Theses results showed that biochar enhances fertilizer use efficiency [77]. Likewise, biochar co-applied with inorganic NPK improves soil quality, leading to better plant height, leaves number and yield of crops such as cowpea and rice [35,78]. Additionally, biochar mixed with minerals or organic amendments effectively reduces a significant portion of nitrogen losses to the environment [53,58,70]. High nitrogen losses from agricultural areas lead to reduced yields and add to economic and environmental costs [79]. Numerous studies have shown that biochar mixed with minerals or organic amendments leads to increased land use and crop yields while significantly reducing nitrogen losses through leaching and emissions [55,58,80]. Tan et al. [81] found that cumulative N2O emissions decreased by 33.7% when rice husk biochar + NPK fertilizer was applied to soils compared to the treatment where NPK fertilizer was applied without biochar.

5. CONCLUSION

The study demonstrated that the use of cashew nut shell biochar, cattle manure, and urea as soil amendments can significantly improve growth and yield of lettuce cultivation in North and Central Benin. Among the treatments involving biochar, the combinations of biochar, cattle manure, and urea (10 t ha^{-1} biochar + 0.025 t ha^{-1} urea +10 t ha^{-1} cattle manure) and biochar and cattle manure (10 t ha^{-1} biochar + 20 t ha^{-1} cattle manure), consistently resulted in an increasing of 318% and 165% of yield across both sites compared to the producers' mineral fertilization practices. This combination also enhanced plant growth parameters, including height and leaf number, thereby contributing to sustainable lettuce production. Given the abundant availability of cashew nut shells in the region, promoting the adoption of their derived biochar in addition to cattle manure, by reducing mineral fertilizer rates and dependence on cattle manure, could lead to more sustainable and profitable lettuce production systems in the region. Future research should focus on the economic profitability and the impact of these practices on soil fertility to further validate these findings. Additionally, studying the best application methods and rates for different soil types and crop systems can help in maximizing the benefits of biochar.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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