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Farmer-managed French bean biochar trials in Rwanda: Effects on yield and soil nutrients

S. Uwingabire[1], J. Nduwamungu[2], G. Nyberg[3], S.A.O. Chamshama[4]*

***Corresponding author:** bisoso05@yahoo.fr

Abstract

In pursuing sustainable and environmentally friendly agricultural practices, using biochar derived from Top-Lit Up-Draft (TLUD) stoves in agriculture has gained significant interest. Biochar (B) from TLUD was applied in furrows in 60 kitchen gardens of French beans (*Phaseolus vulgaris*) using randomized paired design at a rate of 3 tons/ha in Rwanda's Huye and Bugesera districts. Data on yield and the soil properties were collected and analyzed using One-way analysis of variance (ANOVA) within a generalized model in R, followed by Tukey's test ($P<0.05$). The results showed a consistently positive response in French bean yield following a one-time biochar application in both sites. In Bugesera, yields were 21.6 t/ha in season 1, 24.1, and 28.8 t/ha in season 3. In Huye, yields were slightly lower with 21.6t/ha, 24.3t/ha and 27.3 t/ha for season 1,2 and 3 respectively. The soil's chemical properties in treated and control plots ranged as follows: pH 4.9–7.4, available phosphorus 1.3–8.3 ppm, total nitrogen 0.1–0.4%, calcium 3.3–7.6 cmol$_+$/kg, magnesium 0.04–1.7 cmol$_+$/kg, potassium 0.02–0.7 cmol$_+$/kg, and cation exchange capacity 7.3–13.3 cmol$_+$/kg. Biochar application significantly increased soil porosity by 15.2% and plant-available water by 24.1%, while reducing soil bulk density by 15.3% compared to the control. It is evident from the results that biochar improves soil fertility, boosts french bean yield, and support sustainable farming and energy practices. This technology promotes the use of biochar in soil management and suggests that adopting TLUD stoves can enhance energy sustainability by reducing fuel consumption.

Keywords: *TLUD stoves, soil properties, French bean yield, biochar, smallholder farmers, Rwanda*

[1] Regional Research School in Forest Sciences (REFOREST), College of Forestry, Wildlife and Tourism, Sokoine University of Agriculture

[2] Department of Forestry and Nature Conservation, University of Rwanda; Musanze 210, Rwanda

[3] Department of Forest Ecology and Management, Swedish University of Agricultural Sciences; Umea 7070, Sweden;

[4] Department of Ecosystems and Conservation, Sokoine University of Agriculture; Morogoro 3010, Tanzania;

Introduction

Soil fertility degradation is one of the root causes of low yields and nutrient deficiencies in the highlands of East Africa, including Rwanda (Uwiragiye *et al.*, 2022; Mulualem *et al.,* 2021). In Rwanda, soil nutrient depletion, acidity, organic matter depletion, and low CEC increase soil infertility. This is due to soil erosion from intensive agriculture (two seasons per year), high altitude (>60 m asl), poor management practices, and high nutrient removal in the tropics (Kabirigi *et al.*,2017). All these are mainly the effects of high population density (more than 400 inhabitants/km^2) (Bucagu *et al.*,2014).

The increasing use of fertilizers (inorganic and organic), liming of acidic soils (Nduwumuremyi *et al.*,2017), and the promotion of agroforestry systems (Mukurarinda *et al.*,2016) have been proposed to alleviate the soil fertility challenge and boost crop/vegetable yields. However, inorganic fertilizers are still challenging due to their high cost and adverse environmental effects (Tittonell *et al.*, 2016; Nduwumuremyi *et al.*, 2017). Despite the high nutrient content in organic amendments such as chicken manure or compost, they mineralize rapidly in the tropics' humid soils (Bol *et al.*,2000). Yet for crop nutrient requirements to be sustained, manure or compost must be applied every season, and this increases labor and costs (Ndambi *et al.*,2019). Furthermore, manure is a limited resource for most small-scale farmers, and they do not have enough to apply to the whole farm.

Biochar is a carbon (C) rich material that can be used as a soil amendment in agricultural soils. Biochar is produced by the thermal decomposition of organic matter in low oxygen settings (Zemanova *et al.*,2017), such as in TLUD stoves, where the gases from wood or other organic materials are used for cooking, and biochar remains a by-product. Applying biochar on farmlands can ensure long-term benefits for soil fertility and crop production improvement. Both positive and negative yield responses have been reported for a wide variety of crops as a result of biochar application to soils (Meena and Prakasha, 2020, Agegnehu *et al.*,2017, Agegnehu *et al.*,2016a, 2016b, Deenik *et al.*,2010). For instance, the addition of manure biochar increased maize yield by 98–150% and water use efficiency by 91–139% (Uzoma *et al.*,2011); the use of oil mallee biochar increased wheat grain yield by 18% (Solaiman *et al.*,2010); and the applications of bio-char and co-composted biochar-compost increased peanut yield by 23% and 24% (Agegnehu *et al.*,2015a). Moreover, biochar has potential benefits in improving the biophysico-chemical properties of soils. According to Van Zwieten *et al.*,2010), the application of paper-mill biochar at a rate of 10 t/ha in a Ferrosol resulted in considerable increases in pH, CEC, exchangeable Ca, and total C, as well as a reduction in Aluminium availability. In addition, biochar has increased soil fertility, including raising soil pH (Mandal *et al.*,2019), increasing water holding capacity and thus reducing irrigation demand, enhancing root penetration, and changing microbial reactions in soil (Wang *et al.*,2020). Due to the long-lasting stability of biochar in the soil, it requires one application only every 10 to 50 years, depending on the amounts applied (Greenberg *et al.*,2019).

However, to produce enough biochar for all agricultural soils in East Africa or on a small-scale farm may be difficult. In addition, biochar has been extensively studied in crops such as maize (Mensah and Frimbong, 2018; Šimansky *et al.*,2019), Kamara *et al.*,2015), its application in vegetable production systems, particularly in smallholder farming context remains relatively limited. For our study, we have concentrated on biochar application to higher value (from a nutritional and economic perspective) vegetables in smaller areas. Hence, we assessed the effect of biochar from household TLUD stoves on vegetable yield and soil quality in different kitchen gardens of smallholder farmers in two agro-ecological zones (AEZs) of Rwanda. We hypothesized an increase in French bean yield, a highly nutritious and marketable agricultural product in Rwanda, and plant available nutrients upon adding biochar. In addition, we hypothesized an increased amount of plant-available water, CEC, and pH by adding biochar and that these effects should be sustained over several growing seasons.

Materials and methods

Description of Study Sites

The farmer-managed field trials were conducted at 120 farmers' kitchen gardens in the Huye and Bugesera districts (Fig. 1). Huye District is characterized by a sub-equatorial temperate climate with an average temperature of approximately 20°C with an average annual rainfall of 1160 mm (Huye District report 2013). The soils in Huye are generally acidic in nature and are saturated with Aluminium (Al^{3+}) cations, suggesting low agricultural production unless fertilizers (organic or mineral) are added (Huye District report 2013). Bugesera District is regarded as a drought-prone region that experiences frequent rainfall deficits, a significant number of dry spells, and an average annual rainfall of 943 mm; it has an average temperature of approximately 27°C (Benimana *et al.*,2015). The soils in the Bugesera region are shallow to reasonably deep, clayey, sandy clay, or sandy silt (Mikwa *et al.*, 2014).

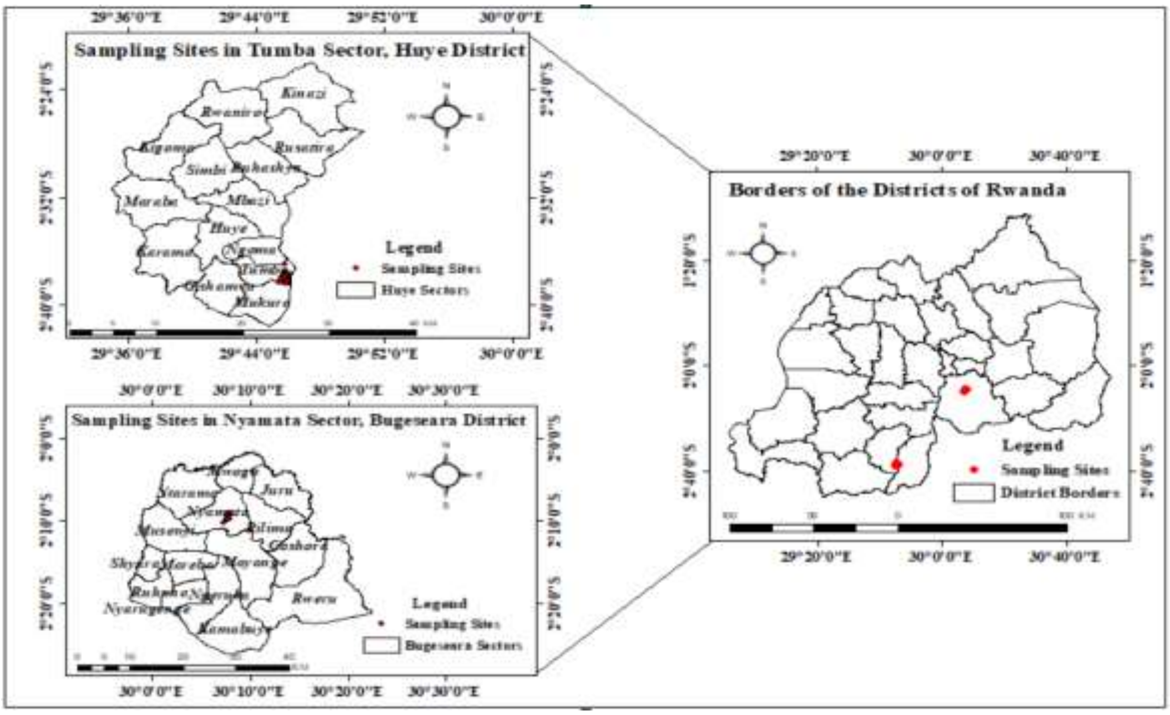

Fig 1. Map of the study areas

Experimental Setup

The field experiment was run over three seasons from September 2022 – September 2023. The trials were conducted at 60 farms (kitchen gardens) in each district, with a single vegetable French beans (*Phaseolus vulgaris*) being grown. French beans are crucial for smallholder farmers due to its economic and nutritional benefits. They can be grown on small plots of french been may be grown on small land where farmers may use limited resources such biochar at low rate of application, yet they benefit with good yield. At each field, the treatments were arranged in a randomized paired design, and the plot size was 3 m^2, where one plot received biochar while the other plot was considered a control. The biochar was applied in furrows (2-3 cm deep) one week before sowing at 3 tons/ha, weeding activities were carried out after two weeks, and pests and diseases were controlled using the recommended pesticides.

Biochar preparation and analysis

The TLUD gasifier cookstoves were provided to smallholder farmers in the Huye and Bugesera districts (Fig. 2). Based on the principle of TLUD technology (McLaughlin 2010), farmers received training on how to use the stove and were required to save the biochar produced for use in participatory on-farm field experiments in the next planting season (French beans in kitchen gardens). *Eucalyptus* fuelwood was used as feedstock. Random sampling design has been used to collect biochar across 30 different kitchen gardens in each site, and 15 samples have been collected, grounded and sieved at <0.154 mm for their chemical analyses. The properties of the biochar were evaluated using the American Society for Testing and Materials methods (ASTM, 2018).

Figure 1. (a) Top Lit UpDraft gasifier stove. (b)stove parts: b1 =outer cylinder, b2 =extinguisher, b3 =inner fuel canister 4=top plate, b5 =ash collector, b6 =pelle

Soil sampling and analysis

Four random soil samples per plot (0-20 cm depth) were mixed to make a composite and collected for further analysis. Soil pH was measured potentiometrically in water and 1N Potassium chloride (KCl) at 1:2.5 soil: water and KCl (Okalebo, 2002). The Total Nitrogen (TN) was determined using the Kjeldahl method (Bremmer and Mulvaney, 1982), while available P was measured using the Bray 1 method (Okalebo, 2002). Exchangeable bases were extracted using one molar of Ammonium acetate (NH_4OAc) (Thomas, 1982), with its concentration being measured using the Atomic Absorption Spectrophotometer. Organic C was determined through the Walkley and Black wet oxidation method (Nelson and Sommers, 1982). Particle size analysis was determined using the Bouyoucos hydrometer method after dispersion with 5% Sodium hexametaphosphate (NSS, 1990), and textural classes were determined using the United States Department of Agriculture (USDA) textural class triangle (USDA, 1975). Bulk density was determined through the core method (Black and Hartge, 1986). Available water was determined using a sand kaoline box and pressure apparatus (NSS,1990).

Determination of Yield of French Beans

Green pods were harvested from each unit plot at regular intervals, and their weight was recorded. As harvesting was done at different intervals, the total weight of pods per season was recorded for each unit plot and was expressed in kilograms (kgs). The green pod yield per plot was converted to yield per hectare (ha) and was expressed in tons (t/ha). The total number of pods per plant was counted and noted from 5 randomly selected plants. The weight of 5 pods and the average weight per pod was calculated.

Data analysis

We tested for outliers using the Gibs test, removing data larger than two standard deviations. The normality test was done using Shapiro-Wilk's test. The Analysis of Variance (ANOVA) was performed to test for differences in soil parameters across the study treatments and yield across the three successive seasons. Tukey Honest Significance Differences (HSD) post hoc analysis implemented in Tukey (HSD) function at $p < 0.05$ was further performed on the study treatments. All statistical tests were performed using R Studio (Ludecke *et al*., 2021).

Results

Biochar properties

The results of the biochar properties of *Eucalyptus* are summarised in Table 1. *Eucalyptus* biochar indicated a moderately basic pH level, low electrical conductivity (EC), high C, and a low level of basic cations and soil nutrients, such as P and TN.

Table 1. ***Eucalyptus biochar properties (n= 15)***

pH 1:10(H_20)	EC µs/cm	TC %	TN %	C/N ratio	P ppm	K ppm	Ca ppm	CEC Cmol₊/kg	VM %	Ash %
8	115.9	71.8	0.33	217.6	0.09	0.35	0.57	26.4	27.5	0.7

TC: total organic Carbon, EC: electrical conductivity, CEC: Cation Exchange Capacity, TN: total Nitrogen, VM: volatile matter, P: Phosphorus, K: Potassium, Ca: Calcium, Mg: Magnesium.

Yield as induced by biochar application

Green pod yield (the number of green pods and weight per plant of French beans) as influenced by biochar application is shown in Tables 2 and 3. All the biochar treatments showed significantly enhanced total yield (Table 2) and a greater number and weight of pods per plant (Tables 3) than control plants grown in untreated soils. Yields also significantly increased over three consecutive seasons with biochar amendments, while they significantly decreased over the seasons in control plots at both sites (Table 2).

Table 2. ***Green pod yield (t/ha) to biochar input for all growing seasons at each site (Mean±SE) (n=30)***

Treatment code	Bugesera site			Huye site		
	S1	S2	S3	S1	S2	S3
BC	21.6±0.1^{aC}	24.1±0.1^{aB}	28.3±0.09^{aA}	21.6± .14^{aC}	24.3±0.1^{aB}	27.3±0.09^{aA}
C	14.4 ±0.1^{bA}	12.3±0.05^{bB}	8.8±0.02^{bC}	13.8 0.11^{bA}	11.5±0.05^{bB}	8.5±0.02^{bC}

Small letters are used to compare means between the treatments; Capital letters are used to compare seasons; s1, s2, s3: growing season of French beans (45-60 days), BC: biochar plot, C: control plot. SE: Standard Error

Table 3. ***The number of green pods per plant and green pod weight per plant due to biochar input for all growing seasons at each site (Mean±SE) (n=30)***

	Trt code	**Bugesera site**			**Huye site**		
		S1	S2	S3	S1	S2	S3
Pods number	BC	10.4+0.19 ^{aC}	12.4±0.16^{aB}	15.1±0.18^{aA}	5.3±0.13^{bC}	12.7±0.1^{aB}	16.7±0.1^{aA}
	C	7.4±0.1^{aA}	5.9±0.15^{bB}	5.3±0.13^{bC}	6.5±0.1^{bA}	5.5±0.04^{bB}	5.4±0.03^{bB}
Pod weight (g)	BC	65.9±0.4 ^{aC}	67.7±0.43^{aB}	68.9±0.29^{aA}	62±0.13 ^{aC}	66.1±0.06^{aB}	69.8±0.1^{aA}
	C	43.7 ±0.2^{bB}	44.6±0.39^{bA}	45.3±0.15^{bA}	43.4 ±0.1^{bA}	42.3±0.04^{bA}	42.6±0.03^{bA}
Weight/pod	BC	6.3±0.4 ^{aA}	5.5±0.43^{bB}	4.6±0.29^{bC}	11.7±0.13^{aA}	5.2±0.04^{bB}	4.2±0.03^{bC}
	C	5.9±0.2^{cC}	7.6±0.39^{aB}	8.6±0.15^{aA}	6.7±0.1^{bB}	7.7±0.06^{aA}	7.9±0.1^{aA}

Small letters compare means between treatments; Capital letters are used to compare seasons; s1, s2, s3: growing season of French beans (45-60 days), BC: biochar plot, C: control plot. SE: Standard Error, Trt: treatment

Soil properties as induced by biochar application

Table 4 shows the increase in the soil's chemical properties after three successive seasons since biochar application. A significant effect has been observed in soil pH, organic C, and available P and TN (Table 4).

Table 4. *Chemical properties of soils after biochar application in the Huye and Bugesera districts (Mean±SE) (n=30)*

Sites	**Trts codes**	**pH water**	**%OC**	**%TN**	**C/N ratio**	**Av. P (ppm)**
Bugesera	BC	7.4±0.1^{a}	4.06±0.03^{a}	0.3±0.003^{a}	13.9±0.1^{a}	8.3±0.08^{a}
	C	5.9±0.06^{b}	1.5±0.13^{b}	0.1±0.003^{b}	11.5±0.1^{b}	3.5±0.09^{b}
Huye	BC	6.5±0.14^{a}	2.7±0.03^{a}	0.4±0.001^{a}	12.2±0.6^{a}	5.4±0.09^{a}
	C	4.9±0.06^{b}	1.4±0.13^{b}	0.1±0.003^{b}	11.3±0.4^{b}	1.3±0.01^{b}

OC: Organic Carbon; TN: total Nitrogen; AV. P: available Phosphorus. Values followed by similar letters under the same column are not significantly different at $p < 0.05$ according to the Tukey test, Trts: treatments. SE: Standard Error

Table 5 shows a significant increase in base cations such as Calcium (Ca^{2+}), Magnesium (Mg^{2+}), and Potassium (K+) due to biochar application in both sites. Sodium (Na^{+1}) was not significantly influenced by biochar application in either site.

Table 5. *Exchangeable bases and CEC of the studied soils after biochar application (Mean±SE) (n=30)*

		Exchangeable bases cmol$_{+}$/kg				
Sites	Trts codes	**Ca^{2+}**	**Mg^{2+}**	**K^{1+}**	**Na^{1+}**	**CEC (cmol$_{+}$/kg)**
Bugesera	BC	7.6±0.2^{a}	1.7±0.1^{a}	0.72±0.01^{a}	0.04±0.0^{a}	12.7±0.2^{a}
	C	3.6±0.1^{b}	0.04±0.0^{b}	0.02±0.0^{b}	0.03±0.0^{a}	7.6±0.2^{b}
Huye	BC	4.9±0.1^{a}	0.9±0.01^{a}	0.3±0.02^{a}	0.05±0.01^{a}	13.3±0.1^{a}
	C	3.2±0.02^{b}	0.04±0.01^{b}	0.02±0.02^{b}	0.04±0.01^{a}	7.3±0.2^{b}

Mg^{2+}: exchangeable Magnesium, Ca$^{2+:}$ exchangeable Calcium, K^{1+} exchangeable Potassium; Na^{1+}: exchangeable Sodium. Values followed by similar letters under the same column are not significantly different at $p < 0.05$ according to the Tukey test, Trts: treatments. SE: Standard Error

Table 6 shows no significant difference in soil textural classes (clay, sand, and silt) in either site. Soil bulk density has changed from 1.5 g/cm^{3} (moderate) to 1.3 g/cm^{3} (low). In addition, soil porosity and plant available water were both influenced by biochar.

Table 6. *The physical soil properties of studied soils before and after biochar application in the Huye and Bugesera districts (Mean±SE) (n=30)*

		Soil textural classes (%)					
Sites	**Trts codes**	**Clay**	**Sand**	**Silt**	**BD (g/cm^3)**	**% Porosity**	**Available water(mm/m)**
Bugesera	BC	22.5 ± 1.3^{a}	65.5 ± 0.5^{a}	13.2 ± 0.2^{a}	1.3 ± 0.6^{a}	47.6 ± 0.2^{a}	115.8 ± 0.1^{a}
	C	22.5 ± 0.2^{a}	65.5 ± 0.5^{a}	10.1 ± 0.1^{a}	1.5 ± 0.5^{b}	41.3 ± 0.1^{b}	93.3 ± 0.1^{b}
Huye	BC	22.5 ± 0.1^{a}	60.5 ± 0.2^{a}	14.1 ± 0.2^{a}	1.3 ± 0.02^{a}	47.3 ± 0.4^{a}	102.5 ± 0.1^{a}
	C	21.9 ± 0.1^{a}	60.4 ± 0.2^{a}	12.9 ± 0.1^{a}	1.5 ± 0.01^{b}	41.3 ± 0.1^{b}	97.5 ± 0.1^{b}

BD: Bulk density, Values followed by similar letters under the same column are not significantly different at p = 0.05 according to the Tukey test. SE: Standard Error, Trts: Treatments

Discussion

Biochar properties

It is realistic for smallholder farmers to produce enough biochar for application to kitchen gardens while saving much fuelwood (Munoz, (2014); Sundberg *et al.* (2020)). The high pH observed in the biochar used is related to ash enrichment and the rapid charring or carbonization rate that involves high temperatures and limited Oxygen availability. This aids the release of volatile acidic compounds from biomass; by driving off these volatile acids, such as acetic acid and formic acid, the overall acidity of the biochar is reduced, leading to an increase in pH (Yargicoglu *et al.*, 2014). The low EC value in the biochar could be due to increased highly soluble and exchangeable base cations. The high CEC value in biochar produced from Eucalyptus may be due to the high oxygen-containing functional group (Dejene *et al.*, 2019). The high P content could be due to the charring of organic materials, which can highly enhance P availability from plant tissue through the cleaving of organic P bonds, as well as to the P content of the ash (Yargicoglu *et al.*, 2014).

Biochar effect on yield of french beans

Given that a large amount of biochar is required to effectively cover large areas and achieve a reasonable yield, which can be challenging, it would be more beneficial to focus biochar applications on smaller, and targeted areas. Concentrate biochar use on plots where a farmer grow higher-value crops or vegetables is a good strategy that may allow him/her to apply biochar in manageable, realistic amounts while maximizing its benefits and improving the productivity and profitability of his or her farm. Typically, the kitchen gardens of smallholder farmers are nutrient-rich soils due to the continuous application of household wastes such as ash from the kitchen and food scraps, among others. In our study, biochar has proven to enhance soil pH, thereby making soil nutrients more accessible and consequently increasing French bean yields. Moreover, biochar increases porosity (Table 6) with micropores, which increases water retention, acts as a habitat for microorganisms, and increases soil biological activity, thereby enhancing soil aggregation. The higher activity of soil microorganisms can increase the availability of nutrients in the soil, which enables plants to absorb adequate nutrients better and increase plant production (Widowati, 2010; Akhil *et al*., 2021). In addition, the yield increase in our study areas was likely partly due to a fertilization effect with the ash as a source of nutrients (Tables 1, 4, and 5), specifically, basic cations and P and the liming effect of biochar. The increase in crop/vegetable yield with biochar application has been reported in the literature (Das *et al. 2020;* Singh *et al., 2019*; Jeffrey *et al*., 2019; Danso and Agyare, 2021). Singh *et al.* (2019) reported that applying rice husk biochar in wheat crops improved the yield and water-holding capacity. El-Naggar (2019) also reported that the number of pods per plant (*Phaseolus vulgaris*) increased with biochar application. Significant horticultural responses to biochar were observed not only in acid soils (Jeffrey *et al*. 2017; Bolan *et al*., 2022) but also in neutral and alkaline tropical soils, as found in other vegetable crops (William *et al*., 2023).

Biochar effect on soil properties

The amended plots showed a significant increase in pH compared to the control plots. The increase in soil pH caused by biochar application may be due to the high surface area and porosity of biochar, which increases the CEC of the soils. This will increase Al (Aluminium) and Iron (Fe) binding to soil exchange sites. Additionally, the ash (e.g., alkaline oxides, carbonates) can increase soil pH by providing greater alkalinity (Vassilev *et al.*, 2013a). The ability of biochar to neutralize acidity has been confirmed in several studies (Zhao *et al.*, 2015; Paz-Ferreiro *et al.*, 2020), stating that biochar can increase the pH of acidic soils, reducing Al toxicity and increasing nutrient availability. Shetty *et al.* (2020) and Martinsen *et al.* (2015) reported that soil pH increased from 4.7 to 8.5 by adding biochar. Moreover, in tropical Kenya, where biochar was used at 50+50 Mg/ha in the first two seasons, soil pH increased significantly, from 4 to 7, in the following years (Kätterer *et al.*, 2019).

The increase in exchangeable bases and CEC was due to the high CEC of biochar (Table 1), which favors nutrient retention, mainly Ca, Mg, K, Fe, and Manganese (Mn), against leaching loss, thus increasing their efficient use by plants. The non-significance of Na in the soil treated with biochar is most likely because biochar doesn't contain Na, and once applied to soils, all the Na is adsorbed, which increases the exchangeable Mg and Ca, to replace Na in the soil and makes it less alkaline. Using (30 t/ha) of coffee husk biochar to degraded sandy loam soil in Nigeria doubled the soil CEC from 19.1 to 40.4 cmol/kg (Adekiya *et al.*,2020).

The findings show a significant influence of biochar on soil TN in the biochar-treated soils (Table 4). Biochar does not provide many nutrients to the soils; instead, it increases their availability by increasing pH. Another reason could be the ability of French beans to fix N. N-fixation from beans and N kept available by biochar (an-ion binding) avails N to plants (Singh *et al.*, 2023).

The increase in available P (Table 4) from biochar application could be attributed to the presence of soluble and exchangeable phosphate in the biochar ash component and the soil pH improvement (Mensah *et al.*, 2017). In agreement with this, Agegnehu *et al.* (2015) and Naeem *et al.* (2018) have reported more significant available P contents in biochar-amended soils than in unamended soils. This improvement was attributed to biochar's ability to retain and exchange phosphate ions due to its positively charged surface sites.

The increase in organic C in both sites following biochar application is due to high amounts of C in the biochar used (Table 1). The soil microorganisms do not as readily degrade compounds found in biochar (it can be sequestered in the soil in the long-term, i.e.,>100 years), as happens for organic material that is not pyrolyzed (Weng *et al.*, 2017; Wijitkosum *et al.*, 2019; Tisserant *et al.*,2019; Ajayi *et al.*, 2016).

The improvement of soil bulk density after biochar application is due to the low density of biochar itself (<0.6 g/ cm^3 for biochar and ~1.5 g /cm^3 for soil), which reduces the density of the bulk soil through the mixing or dilution effect (Humberto Blanco-Canqui (2017), and to increased soil aggregation (Burell *et al.*, 2016). As expected, the decrease in soil bulk density caused by biochar application directly increased soil porosity (Table 6). Biochar particles have a 70 to 90% porosity, and adding this porous material to the soil can concomitantly increase soil porosity.

Biochar has significantly increased plant available water compared to control plots (Table 6). This is due to the particular surface area of biochar (>3000 m^2/g), which is much higher than soil (10 to 40 m^2/g for sandy loam soils, 5 to 150 m^2/g for silt loam soils, and 150 to 250 m^2/g for clayey soils). Hence, adding biochar to soil can alter total porosity, pore size distribution, water transmission, and water retention characteristics (Githinji, 2013; Uwase, 2022).

Conclusion

Biochar increases soil organic C and can do so over extended periods, making it pertinent to the international carbon sequestration and climate change discourse. Biochar also raised soil pH, increased CEC and nutrient availability (mostly P, which has strong interactions in acidic soils), and decreased soil bulk density; it increased soil porosity and plant available water, which could be a good sign for water use efficiency. The technology reduces the need for lime and inorganic fertilizers through improved soil properties. Our results show a significant increase in the yield of French beans over three consecutive seasons. The increased vegetable yield can improve nutrition and farm economics in local communities and eventually enhance the adoption of the TLUD stoves, which will ensure energy sustainability. Therefore, biochar application can be recommended, especially to smallholder farmers, for sustainable agriculture/agroforestry. There is potential for concentrating biochar to produce nutrients/high-value crops/vegetables. Longer-term effects shall be investigated to assess the effect of B on soil quality and crop/vegetable production using diverse feedstocks available in the Rwandan landscape to produce Biochar. Sustainability of biomass availability may be strengthened throught the promotion of agroforestry adoption among smallholder farmers.

Data Availability

Data will be made available on request

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Declaration of competing interests

The authors declare that they have no known competing interests.

Credit Authorship Contribution Statement

US conceptualized the study, conducted fieldwork and laboratory analyses, and wrote manuscript drafts. JN, GN, and SAOC conceptualized the study, commented on drafts, and contributed to the writing. All the authors contributed to the final manuscript.

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