Article

Not peer-reviewed version

Combining Charcoal Application and *Tithonia diversifolia*-Based Agroforestry to Achieve Sustainable Maize Production on Smallholder Farms in Kinshasa, DR Congo

Joseph Reagan Nitu Falasi * , Rajpal Shetty , Jean-Baptiste Djétchi Ettien , Erik Meers

Posted Date: 12 June 2026

doi: 10.20944/preprints202606.1052.v1

Keywords: charcoal; *Tithonia diversifolia*; agroforestry; maize; Sub-Saharan Africa

doi:10.20944/preprints202606.1052.v1

Article

Combining Charcoal Application and *Tithonia diversifolia*-Based Agroforestry to Achieve Sustainable Maize Production on Smallholder Farms in Kinshasa, DR Congo

Joseph Reagan Nitu Falasi [1,2,*], Rajpal Shetty [3], Jean-Baptiste Djétchi Ettien [2] and Erik Meers [3]

[1] Faculté des Sciences Agronomiques et Environnement, Université de Kinshasa, Kinshasa P.O. Box 127, Democratic Republic of the Congo
[2] UFR STRM, Université Félix Houphouët-Boigny, Abidjan P.O. Box 582, Côte d'Ivoire
[3] Department of Green Chemistry and Green Technology, Faculty of Bioscience, Ghent University, Gent P.O. Box 9000, Belgium
* Correspondence: reagan.falasi@unikin.ac.cd

Abstract

Improving soil fertility in the context of climate change is of paramount importance. This study addresses this challenge in Kinshasa (DR Congo) where the combined effect of charcoal waste and *Tithonia diversifolia* biomass was evaluated in an alley cropping trial, with two successive maize crops. The objective was to sustain optimum maize yields, and to derive insights into sub-Saharan Africa (SSA). Three treatments were applied: a control (T0) plots; and two other plots receiving 5 t ha^{-1} of charcoal prior to cultivation combined with alley cropping using *T. diversifolia* pruned in situ at 50 cm (T1) or at 100 cm (T2)) and applied as mulch. The results showed that *Tithonia* biomass production reached approximately 100 t DM ha^{-1} year^{-1}. Maize grain yields in the first season were higher in the amended plots (2.7 to 2.9 t ha^{-1}) compared to the control (1.6 t ha^{-1}). The yields obtained in the second season were similar for all plots, but they declined significantly for T0 compared to the first season. While yields stabilized with amendments, they stayed below SSA self-sufficiency targets (4.45 t ha^{-1}). Improving crop N absorption and use efficiency, which were low in this study, is key to closing the yield gap.

Keywords: charcoal; *Tithonia diversifolia*; agroforestry; maize; Sub-Saharan Africa

1. Introduction

In most Sub-Saharan African (SSA) countries, crop yields are lower than their potential due to various constraints, including low soil nutrient availability, particularly nitrogen (N) and phosphorus (P). The low N content of SSA soils is primarily attributed to their low soil organic matter (OM) content (typically 2–4% OM), which limits nutrient availability [1–5]. As for P, despite a substantial total P stock in the top meter of soil (562.9 g m-^{2}), most of this nutrient is unavailable to crops due to adsorption by iron (Fe) and aluminum (Al) oxides [6–9]. Furthermore, continuous cultivation in the same locations leads to progressive nutrient depletion, particularly when crops are grown with little or no external inputs [2,9]. Mineral fertilizers are not widely used in SSA due to their limited availability and high cost in this region [10], while organic amendments of animal origin are also scarce [11]. Regarding plant-based amendments, which are more readily available, the required application rates are high (5-10 t DM ha^{-1} year-1) due to their low N content (<2.5% N) and the rapid decomposition of organic matter in soils [12–15]. Thus, these plant-based products do not provide enough organic matter to maintain soil fertility. Consequently, the total nutrient inputs (N, P & potassium (K)) applied by smallholder farmers from all sources rarely exceed 10 kg ha^{-1} [5].

doi:10.20944/preprints202606.1052.v1

Maize is one of the most important crops in Africa yet yields remain low and production is insufficient. Increasing current yields by 50-75% is necessary to meet both present and projected demands by 2050 [5,16]. To increase maize grains yields and sustain production, it is necessary to implement the most effective combination of agroecological practices adapted to the SSA context [17,18]. This may include the application of OM, like biochar or charcoal, and labile, nutrient-rich biomass such as *Tithonia diversifolia*. *T. diversifolia*, which grows rapidly, is well adapted to tropical conditions and has a high K content (>4%), with N and P contents greater than the net immobilization threshold (N>2.5%, P>0.25%), as well as appreciable micronutrient levels, and dry matter production of 7-15 t DM ha^{-1} year^{-1}. Despite their low N content (notably plant-based biochar), biochar can provide crops with significant amounts of K, and sometimes P. They can also enhance soil P availability by reducing its adsorption and promoting its release into the soil solution [19–24], as well as improving soil pH, CEC and other properties [25]. Likewise, previous studies have shown that the effects of applying labile organic amendments or black carbon individually to soils and crops are limited compared to those from their combination which creates beneficial synergistic effects on soils and crops [21,26–29].

However, several knowledge gaps identified in the previous studies need to be addressed. Regarding *T. diversifolia*, its use requires cultivation to produce sufficient biomass for fertilization, notably by alley cropping with crops. But if this system is not well managed, the crops might suffer from allelopathy and competition due to the presence of the hedges. In addition, there is a risk that biomass from plantation may be less rich in nutrients than in natural hedgerows [21,30–34]. Hence the need to target agricultural practices that can ensure abundant *Tithonia* production and its nutrient richness on the one hand, and that can maximize positive interactions between hedgerows and crops on the other. As for biochar, it is important to assess its effects under SSA conditions, where farmers more commonly use charcoal rather than biochar, and typically at low application rates (less than 1 t DM ha^{-1} year^{-1}) [16,24,35].

The objective of this study is to test the effectiveness of a system combining charcoal application and *T. diversifolia*-based agroforestry to sustain optimum maize yields, and to derive insights relevant to SSA.

2. Materials and Methods

2.1. Description of the Experimental Site

The field study was conducted in Kimwenza, at Mafumfu village (S 04°30.695′, E 015°15.379′, at an altitude of 390 m), in the southwestern part of Kinshasa (DR Congo). Kinshasa has a hot and humid tropical climate (AW$_4$ according to the Köppen-Geiger climate classification), with an average dry season of four months (June to September) and one rainy season [36]. Soils of Kinshasa are among the most desaturated tropical soils (Kaolinite rich soils). In particular, the Kimwenza area is characterized by a mixture of Arenoferralsols and Haplic Acrisols [3,4,37,38]. The soil in the experimental site was dominated by the sandy fraction (more than 90% sand and a maximum of 2% clay) and its main chemical characteristics are presented in Table 1.

Table 2. Chemical characteristics of the experimental soil.

Properties	Soil depths (cm)	
	0-20	**20-40**
Water-pH	5.77	5.58
KCl-pH	4.31	4.58
OM (%OC x 1.724)	1.2	1.4
Total N (mg kg^{-1})	590	620
NO_3-N (mg kg^{-1})	2.23	2.42

NH_4^+-N (mg kg^{-1})	45.84	38.6
Total P (mg kg^{-1})	134.2	136.4
Available P (mg kg^{-1})	18.3	15.4
Total K (mg kg^{-1})	229	250
Exchangeable K (Cmol(+) kg^{-1})	0.06	0.02
Total Mg (mg kg^{-1})	141	168
Exchangeable Mg (Cmol(+) kg^{-1})	0.37	0.67
Total Ca (mg kg^{-1})	377	371
Exchangeable Ca (Cmol(+) kg^{-1})	1.30	1.63
Total S (mg kg^{-1})	75.2	67.8
Total Fe (mg kg^{-1})	6084	4990
Total Mn (mg kg^{-1})	39.31	64.11
Total Zn (mg kg^{-1})	8.36	6.16
Total Cu (mg kg^{-1})	1.42	1.30
DCB Fe_2O_3 (mg kg^{-1})	3475.8	3800.5
DCB Al_2O_3 (mg kg^{-1})	984.9	1116.1
ECEC (Cmol(+) kg^{-1})	1.4	2.9

OM: organic matter, OC: organic carbon, DCB Fe2O3 and Fe2O3: total iron and aluminum oxides.

2.2. Experimental Setup

The experiment consisted of a block design with three treatments and three replicates, in essence nine plots (9 m x 3 m each). Three treatments were applied: a control (T0) plot without any amendments; and two other plots receiving 5 t ha^{-1} of charcoal prior to cultivation combined with alley cropping using *T. diversifolia* pruned insitu at 50 cm (T1) or at 100 cm (T2) and applied as mulching. Maize was cultivated continuously for three successive cropping cycles at the experimental site, with the last one being ravaged by insects. The amounts of *Tithonia* biomass applied as fresh mulch (without drying) during the three cropping cycles in treatments T1 and T2 were 13.15, 5.12, and 9.15 t ha^{-1}, respectively. Concretely, for some pruning, the harvested leaves and young stems were weighed and divided equitably among the different plots of T1 and T2. Although the amounts of *Tithonia* biomass applied to plots T1 and T2 are similar, we hypothesized that the interactions between the hedges and the crops should be affected by the difference in pruning height [32,39,40].

A summary of the treatment composition is given in Table 3.

Table 2. Experimental Treatments.

Treatments	**Charcoal application rate (t ha^{-1})**	**Length of lateral branches of *T. diversifolia* after pruning (cm)**
T0 (Control)	0	-
T1	5	50
T2	5	100

T. diversifolia was planted using cuttings that were 20 cm long in April 2023 at 250,000 plants ha^{-1}, as recommended in DR Congo. Maize was sown two weeks later, between two hedges of *T. diversifolia*, with the crops separated by one meter. The maize varieties used were UPN1 for the first crop and SC 719 Tembo for the second. Since the first maize crop was sown in the same month with *T. diversifolia*, its initial fertilization came from the biomass of *T. diversifolia* pruned from natural hedges. Based on observations of the growth of *T. diversifolia*, pruning was carried out eight times from June 2023 to July 2024 [41,42].

The charcoal was collected in Kinshasa, crushed and sieved. The particles measuring less than 2 mm in diameter were applied to fields at an application rate of 5 t ha^{-1} and at a depth of 20 cm [43,44]. It was a mixture of charcoal particles originate from a carbonization site (Batéké Plateau) and two sales sites (Mikondo and Liberté Markets) to the east of Kinshasa, where non-marketable particles are discarded in large quantities [45,46].

During weeding, the weeds consisting mainly of *Chromolaena odorata* species, were left in place as mulch in the different plots after being cut. These weeds were more abundant in the T0 plots.

2.3. Laboratory Analyses

Analyses were carried out at the Bioresource Recovery Laboratory of the Department of Green Chemistry and Technology of Bioscience Engineering at Ghent University, Belgium. For *T. diversifolia*, it should be noted that this was a composite sample of young leaves and young stems. Measurement of quasi-total elements in the soil samples was carried out after digestion in aqua regia using a hot plate and ICP-OES (Thermo Scientific ICAP PRO) [47]. For the plant samples and charcoal, ICP-OES measurements were carried out after microwave-assisted digestion (Milestone Connect device) using concentrated HNO_3 and aqua regia, respectively [48,49]. In all samples, the total N and total carbon (TC) were measured using the CN analyzer (Primacs100 Analyzer series), while inorganic carbon (IC) determination was carried out by acidification. The total OC content was calculated by subtracting the IC from the TC content [50,51].

The pH of the soil and charcoal was measured using a pH electrode meter (Thermo Scientific/Orion Star A211). NO_3^--N and NH_4^+-N concentrations in soil and charcoal samples were measured using a segmented flow analyzer (Seal Analytical VVI15156R) after extraction with 1 M KCl [52]. The effective cation exchange capacity (ECEC) and the content of exchangeable bases (Mg, Ca, K and Na) in soil and charcoal samples were measured using cobalt hexamine trichloride (Cohex) for extraction and measurement by ICP-OES [53].

For soil samples specifically, the available P content was determined using a Bray 2 solution (0.03 M NH_4F + 0.025 M HCl) [54]. This method was slightly modified for analysis by ICP-OES instead of spectrophotometry using molybdenum blue, which is commonly done [55]. Additionally, DCB (dithionite-citrate-bicarbonate) was employed for the extraction of free Fe and Al oxides [56]. This method was also modified in view of the ICP-OES measurement instead of spectrophotometry (colorimetry) or atomic absorption spectrophotometry. Soil texture was evaluated using the hydrometer method [57]. Available P content of charcoal was evaluated using 2% citric acid [52,58] and ICP-OES.

2.4. Statistical Analysis and Other Calculations

All data were analyzed under ANOVA system. Regarding *T. diversifolia* biomass, the comparison involved the sum of the quantities obtained in 2023 (April to December) versus those from 2024 (January to July), according to the two pruning heights (50 or 100 cm). For the maize crops, grain and straw yields for the first two seasons were compared for the different treatments within the same season and for the same treatment between the two seasons. Data on the chemical composition of charcoal and *Tithonia*, as well as data relating to *Tithonia* biomass production and the application rates of *Tithonia* and charcoal applied in the soil were used to evaluate the quantities of nutrients (N, P and K) supplied to maize crops.

3. Results

3.1. Production of Dry Biomass of T. diversifolia from April 2023 to July 2024

Pruning height had no effect on *T. diversifolia* biomass production during the 16-month period, regardless of when measurements were taken. The *Tithonia* production obtained over 16 months was 125.56 t ha^{-1} for T1 (48.3 t ha^{-1} from April to December 2023 and 77.26 t ha^{-1} from January to July 2024) and 98.71 t ha^{-1} for T2 (38.49 t ha^{-1} from April to December 2023 and 60.22 t ha^{-1} from January to July

2024). The production values for the two treatments and periods are not significantly different at the 5% probability threshold (p-value=0.39). However, the values obtained suggest an increasing production trend over the two periods (Figure 1), that is 59.94% for T1 and 56.41% for T2.

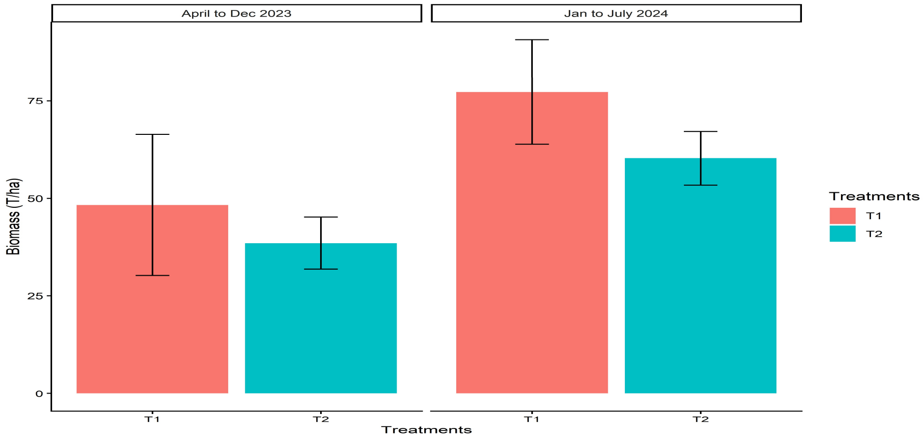


Figure 2. Biomass production of Tithonia according to pruning heights and periods.

3.2. *Chemical Composition of Charcoal Used*

The chemical composition of the charcoal used is presented in Table 4. The charcoal used is slightly acidic. The concentration of available N (NO_3^--N content + NH_4^+-N content) would equal 0.045 g kg^{-1}. Moreover, the available K content, which on average is equivalent to 38.13% (11.43 to 58.82%) of total K according to the literature [59], would be 0.82 g kg^{-1} for the charcoal tested. Furthermore, considering this chemical composition, the application rate of 5t ha^{-1} during the experiment would add 0.225 kg of available N, 2.029 kg of available P and 4.1 kg of available K to the soil.

Table 5. The chemical composition of the charcoal added to the experimental soil.

NH_4^+-N (g kg^{-1})	NO_3^--N (g kg^{-1})	Available P (g kg^{-1})	Total K (g kg^{-1})	Total Mg (g kg^{-1})	Total Ca (g kg^{-1})	Total S (g kg^{-1})	Water-pH	ECEC (Cmol+ kg^{-1})	OC (%)
0.013 ± 0.0007	0.028 ± 0.0025	0.41 ± 0.017	2.34 ± 0.11	0.94 ± 0.03	5.24 ± 0.18	0.35 ± 0.02	6.71 ± 0.05	9.5 ± 0.95	42.03 ± 1.73

Available P: P extracted with 2% citric acid.

3.3. *Chemical Composition and Mineral Exports of T.diversifolia*

The dry matter content was 25% for *T.diversifolia* leaves, 33% for green stems, and 28.7% for the entire trimmed biomass. Moreover, the proportion of leaves and stems in the dry weight of *Tithonia* was 46% and 54%, respectively. Information on the chemical composition of *Tithonia* is presented in Table 6.

Table 7. Chemical composition of T. *diversifolia.*

Organs	N (%)	P (g kg^{-1})	K (g kg^{-1})	Mg (g kg^{-1})	Ca (g kg^{-1})	S (g kg^{-1})	Fe (g kg^{-1})	Zn (g kg^{-1})	B (g kg^{-1})	Mn (g kg^{-1})	Total C (%)
Young leaves	2.96 ^{a} ± 0.11	2.59 ^{a} ± 0.06	34.77 ^{a} ± 1.77	3.06^{a} ± 0.06	14.95^{a} ± 0.06	2.62^{a} ± 0.04	0.52^{a} ± 0.02	0.07^{a} ± 0.00	0.01^{a} ± 0.00	0.24 ^{a} ± 0.00	39.84 ^{b} ± 0.85
Young stems	0.99 ^{b} ± 0.02	0.82 ^{b} ± 0.02	12.4 ^{b} ± 0.26	1.4 ^{b} ± 0.03	2.69 ^{b} ± 0.06	0.59 ^{b} ± 0.02	0.03 ^{b} ± 0.00	0.02 ^{b} ± 0.00	0.01^{a} ± 0.00	0.06 ^{b} ± 0.00	42.5 ^{a} ± 0.19

Means followed by different letters are significantly different at $p < 0.05$.

Apart from bore (B) and TC, *Tithonia* leaves contained significantly higher quantities of mineral elements than the stems. In addition to elemental concentrations, leaves and stems are also differentiated by the order of importance of these elements.

Considering the proportion of leaves and stems in the *Tithonia* biomass mentioned above, the concentrations of the main nutrients in the biomass are 1.904% N, 0.1639% P and 2.278% K. Based on these concentrations, the exports are 2,390.66 kg N ha^{-1}, 205.79 kg P ha^{-1} and 2,860.26 kg K ha^{-1} for T1, according to the quantities of *Tithonia* biomass harvested (see Appendix A).

3.4. Amount of Nutrients Supplied to Crops by Tithonia and Charcoal

The quantities of nutrients supplied to crops depend on the application rates of charcoal and *Tithonia*, their chemical compositions, and the recovery rates of each nutrient by crops. For the three main nutrients, the recovery rates by maize crops have been estimated at 25% for the first crop and 10% for the second crop in the case of their supply via *Tithonia* biomass, according to [14]. Thus, considering the *Tithonia* application rates, the amounts of nutrients supplied were calculated for the first (62.59 kg N, 5.4 kg P, 74.9 kg K ha^{-1}), second (49.4 kg N, 4.21 kg P, 59.05 kg K ha^{-1}) and third maize crops (53.25 kg N, 4.57 kg P, 63.7 kg K ha^{-1}) (see Appendix B).

Regarding charcoal, we have assumed that the first crop absorbs the entirety of the soluble forms of N, P and K whose quantities were calculated previously (0.225 kg of available N, 2.029 kg of available P and 4.1 kg of available K). Therefore, we considered that the amounts of N, P and K potentially absorbed by the first maize crop were equal to the sum of those supplied by charcoal and *Tithonia* biomass.

3.5. Changes in Soil Properties

The properties of the experimental soil at the end of the test are presented in Table 8. The K content in the 0–20 cm layer (T1 = T2 > T0, p-value < 0.05) and the NH_4^+-N content in the 20–40 cm layer (T1 = T2 > T0, p-value < 0.05) are higher in the soils of the two treatments amended compared to the control. The increase in K content in the topsoil layer of the amended soils was 50.47% and 52.08% for T1 and T2, respectively. As for the increase in NH_4^+-N concentration in the 20–40 cm layer of the amended soils, it is 128.38% for T1 and 113.33% for T2 compared to the control.

For certain properties, the changes observed in the soils of treatments T1 and T2 followed different trajectories. Indeed, compared to T0, the available P content in the 20–40 cm layer is higher for T1, whereas it is lower for T2. Conversely, the OM contents for the 20–40 cm layer are similar for T0 and T2, whereas the value obtained for T1 is lower. This suggests an effect of the pruning height of the associated *Tithonia* hedges, 50 cm for T1 and 100 cm for T2.

The properties for which no significant difference was observed among the three treatments include, notably, ECEC and water pH. This is likely due to the chemical composition and application rates of the soil amendments used.

Table 9. Properties of the experimental soil at the end of the test.

Properties	**0-20 cm**			**20-40 cm**		
	T0	**T1**	**T2**	**T0**	**T1**	**T2**
Water-pH	5.35^{a} ± 0.18	5.72^{a} ± 0.26	5.81^{a} ± 0.29	4.96^{a}± 0.24	4.94^{a} ± 0.13	4.84^{a} ± 0.1
OM (%OC x 1.724)	1.48^{a} ± 0.12	1.59^{a} ± 0.21	1.55^{a} ± 0.19	1.27^{a}± 0.22	0.81^{b} ± 0.09	1.37^{a} ± 0.13
Total N (mg kg^{-1})	600.00^{a} ± 45.8	676.67^{a} ± 60.28	666.67^{a} ± 98.66	366.67^{b} ± 55.08	430.0^{b} ±70.00	646.67^{a} ± 15.28
NO_3^--N (mg kg^{-1})	1.69^{b} ±	5.19^{a} ±	3.70^{ab} ±	4.06^{b} ±	5.70^{a} ±	3.37^{b} ±

	0.06	1.29	0.49	0.16	0.61	0.55
NH_4^+-N (mg kg^{-1})	34.20^{b} ± 5.05	52.92^{a} ± 3.42	33.16^{b} ± 1.6	17.48^{b} ± 3.39	39.92^{a} ± 2.94	37.29^{a} ± 3.94
Total P (mg kg^{-1})	130.93^{b} ± 15.57	222.15^{a} ± 29.40	150.39^{b} ± 9.90	109.45^{a} ± 10.89	128.9^{a} ± 17.01	97.72^{a} ± 8.74
Available P (mg kg^{-1})	40.54^{b} ± 4.7	71.02^{a} ± 7.31	40.78^{b} ± 6.38	16.81^{b} ± 1.53	43.36^{a} ± 5.19	5.78^{c} ± 0.95
Total K (mg kg^{-1})	170.98^{b} ± 18.23	257.29^{a} ± 32.61	260.04^{a} ± 41.37	197.78^{a} ± 23.21	217.5^{a}± 26.92	177.25^{a} ± 21.75
Mg (mg kg^{-1})	118.32^{ab} ± 14.23	159.93^{a} ± 24.60	113.42^{b} ± 10.94	122.50^{a} ± 12.00	132.22^{a} ± 7.59	75.19^{b} ± 9.60
Ca (mg kg^{-1})	318.76^{b} ± 25.27	555.17^{a} ± 34.82	362.11^{b} ± 10.7	159.41^{a} ± 22.57	167.55^{a} ±16.49	130.41^{a} ± 15.54
S (mg kg^{-1})	64.63^{b} ± 7.54	82.96^{a} ± 5.61	76.43^{ab} ± 5.59	59.57^{a} ± 8.62	53.79^{a} ± 4.87	55.97^{a} ± 6.15
ECEC (Cmol(+)kg^{-1})	2.49^{a} ± 0.35	3.01^{a} ± 0.34	2.53^{a} ± 0.33	2.49^{a} ± 0.18	2.49^{a} ± 0.39	1.93^{a} ± 0.27

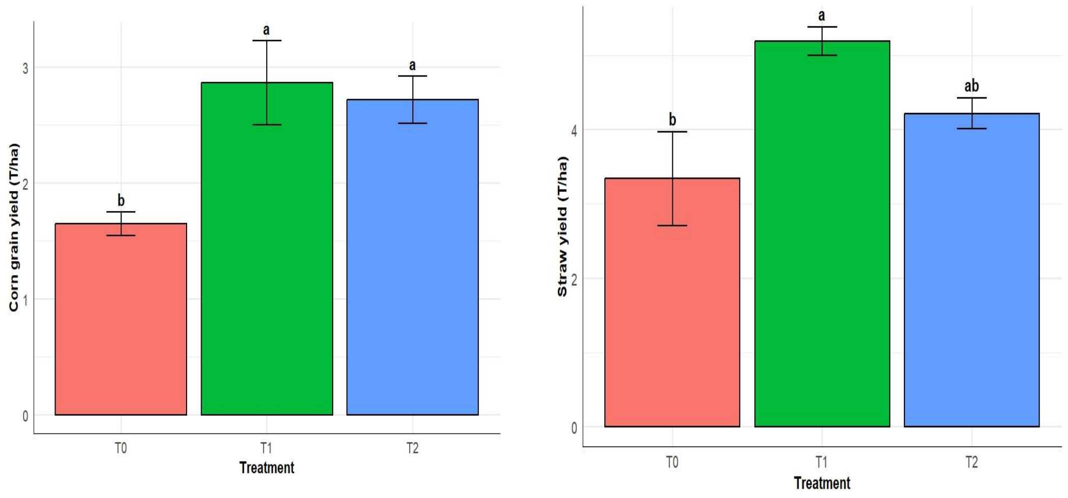
For each depth, means followed by different letters are significantly different at $p < 0.05$.

3.6. Maize Grain Yields and Straw Yields for Both Seasons

Figures 3 (a) and 4 (b) present maize grain and straw yields for the first season. Amended soils (T1 and T2) had the better grain yields (2.7 to 2.9 t ha^{-1}) than the control (1.6 t ha^{-1}, p-value = 0.025). Similarly, the straw yield of T1 (5.19 t ha^{-1}) was higher than that of the control plot (3.34 t ha^{-1}, p-value= 0.038). In the second growing season, grain yields were similar between treatments (p-value= 0.26), while T0 and T1 had different straw yields (p = 0.045) (Figures 5 (a) and 6 (b)).

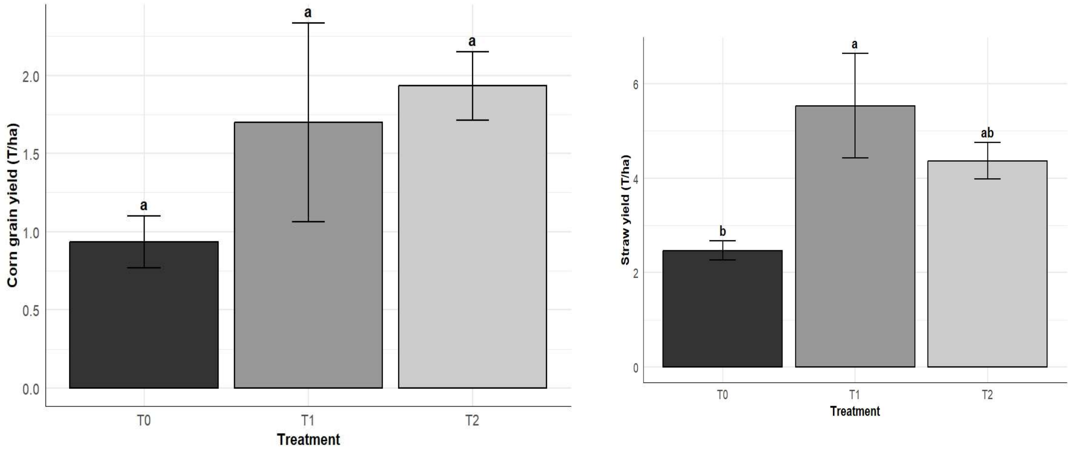
Each treatment was also compared in terms of grain and straw yields obtained during two consecutive seasons. When comparing the grain yields of the same treatments in both seasons, it is evident that the decrease is not significant for the amended treatments T1 and T2 (p-values of 0.2 and 0.06, respectively), whereas the opposite is observed for the control treatment (a p-value of 0.025). This indicates a relative stabilization of maize grain yields from one season to the next following the addition of charcoal and *T. diversifolia*.

Although there were no plots treated exclusively with Tithonia or charcoal to isolate the effects of these two amendments, the stabilization of yields in the treated plots could suggest synergistic effects of the added organic matter, given their potential complementarity.



(**a**) (**b**)

Figure 7. (**a**) Maize grain yields for the first crop; (**b**) Maize straw yields for the first crop.



(**a**) (**b**)

Figure 8. (**a**) Maize grain yields for the second crop; (**b**) Maize straw yields for the second crop.

3.7. Mineral Contents of the Grains from the First Maize Crop

Similar values were observed across the three treatments for the concentrations of NPK in maize grains: approximately 16 g kg^{-1} for N, 3.9 g kg^{-1} for P and 4.5 g kg^{-1} for K (Table 10).

Table 11. Concentrations of NPK in the grains of the first maize crop.

Treatments	N content (mg kg^{-1})	P content (mg kg^{-1})	K content (mg kg^{-1})
T0 (Control)	16.3^{a}	3.93^{b}	4.40^{b}
T1	15.7^{a}	3.98^{a}	4.52^{a}
T2	15.8^{a}	3.94^{a}	4.41^{a}

Means followed by different letters are significantly different at $p < 0.05$.

4. Discussion

4.1. Initial Soil Conditions

This soil is a variable soil charge (water-pH - KCl-pH > 0), which resulted in the weak available P values (15 to 18 ppm). The values of other parameters (total N, total P, OM, etc. See Table 12) are like those of other desaturated tropical soils [4,60–62]. The low NO_3^--N and NH_4^+-N content in comparison to total N, shows that most of the N in this soil is supplied by OM. Therefore, the relative higher level of NH_4^+-N than NO_3^--N could be due to the low nitrification capacity of these soils or NO_3^--N losses through leaching [63].

4.2. Production of Tithonia diversifolia Biomass

Regarding *T. diversifolia biomass*, the fact that the pruning height applied did not significantly influence the amount of dry matter harvested is consistent with the observations of [41] in Ghana. This author observed that biomass production induced by pruning heights of 50 and 100 cm was higher than that observed for the 25 cm height. In contrast, yields associated with the 50 and 100 cm heights were not significantly different. These results suggest that 50-100 cm represents the pruning height threshold below which biomass yield may decrease. Moreover, the trend of increasing production over time is similar to the observations of [42] in Sri Lanka, suggesting that pruning activities will not limit biomass production in the long term. But the dry matter production observed in this study (around 100 t DM ha^{-1} $year^{-1}$) is by far higher than that observed in other works (less than 15 t ha^{-1} $year^{-1}$). This is due to the density of *Tithonia* plants in this study (120,000 versus 30,000 plants ha-1 commonly) and the relatively high dry matter content in this trial (28.7%) than in the other tests (15–25%) [41,42,64,65].

4.3. Nutrient Contents of T. diversifolia Biomass

The nutrient contents of *T. diversifolia* (Table 13) are like those in previous studies and known for natural hedgerows. As in those studies, the nutrient content is comparatively higher in the leaves than in the stems [12,14,31]. Moreover, stems exhibited higher boron (B) and carbon (C) concentrations than leaves. While the trend holds true for C [66], the results for B contradict previous works on the Asteraceae family [67,68] and should be analyzed in future studies.

4.4. Nutrient Contents of Charcoal

For most of the considered properties, the observed values are within the range of those known for biochar. The exception concerns the pH value (6.71), which is lower than the known limits in previous studies (7.28) [52,69]. This would be related to the nature of the trees used for combustion as well as the conditions of charcoal production and storage [70].

4.5. Evolution of Soil Properties

The results of soil analysis after the experiment (Table 14) revealed that the K content in the 0–20 cm layer and the NH_4^+-N content in the 20–40 cm layer, were higher in the plots with amended soils (T1 and T2) compared to the control. This is consistent with the results obtained in a previous study on the combined application of *Tithonia* and charcoals [26]. Considering physicochemical characteristics of each amendment, we assume that the mechanisms involved are the mineralization of *T. diversifolia* biomass and the labile fraction of the charcoals, the positive priming effect of charcoals as well as the protection of nutrients (K^+ and NH_4^+) from various forms of loss, by the mulch of *T.diversifolia* and charcoals which could retain them through new exchange sites or in the micropores [27,40]. This would also indicate that the amounts of N and K supplied through the biomass of *T. diversifolia* and the labile fraction of the charcoals (more than 165 kg N ha^{-1} and more than 200 kg K ha^{-1}) were high enough to meet crop needs and build up reserves in the soil [21,28].

However, for certain properties, the changes observed in the soils of the T1 and T2 treatments followed different trajectories. This is the case for available P content in the 20–40 cm layer, which is higher for T1 compared to T0, whereas it is lower for T2. Similarly, OM contents in the 20–40 cm layer are equivalent for T0 and T2, whereas the value obtained for T1 is lower. According to the results of a previous study, we hypothesized that the modification in available P content depended more on the application of *Tithonia*, which is relatively more concentrated in P than charcoals [26,59]. But the change related to OM is more linked to charcoals application, since the effect of the biomass of *T. diversifolia* on soil OM is known to be generally negligible [21].

Contradictory results between T1 (maize intercropped with *Tithonia* pruned at 50 cm) and T2 (maize intercropped with *Tithonia* pruned at 100 cm) indicate that pruning height might influence soil's properties. Possible mechanisms include the effect on evaporation from the soil surface and the rate of organic matter mineralization, through the shading that the hedges provide over the soils of the associated crops [71]. Another factor could be the underground competition between *T. diversifolia* hedgerows and crops, particularly in relation to the P uptake from the soil, through phosphatase activity [34]. However, the only study conducted on this topic in the Sahel-Sudan zone using the species *Albizia harveyi* and *Albizia versicolor* showed that pruning had no significant effect on soil properties in Tanzania [40]. These observations suggest that additional trials are warranted to clarify this point. Differences in soil properties between T1 and T2 may also reflect differential retention of *Chromolaena* biomass after weeding, as biomass inputs were not necessarily equivalent across amended plots.

Furthermore, no significant differences were observed among the three treatments for several other properties, including ECEC and soil pH. In the case of combining *T. diversifolia* and charcoals, the change in soil pH should linked more with their interaction and with the charcoals which have the liming effect, than *T. diversifolia* alone [21]. The finding that soil pH did not improve in this study could be explained by the low pH of the charcoals used and that of the amended soil [72]. Change in ECEC values is also more related to charcoals compared to *T. diversifolia* [26]. The fact that the soil ECEC value has not improved suggests that these charcoals are deficient in functional groups capable of adsorbing cations in the soil [73].

4.6. Evolution of Maize Grain and Straw Yields, and Grain Mineral Concentrations

Maize grain yields in the first growing season (Figure 9 (a)) were higher in the amended plots (2.7 to 2.9 t ha^{-1}) compared to those in the control (1.6 t ha^{-1}, p-value = 0.0251). Similarly, yields over two consecutive seasons remained stable in the amended plots (p-values of 0.199 and 0.064, respectively, for T1 and T2), whereas they declined from the first to the second season in the control (p-value of 0.025) (Figure 10 (a)). Thus, in this study, the synergistic effect between *Tithonia* and charcoal appears to have improved or stabilized certain soil properties, led to better absorption of certain nutrients in amended plots, and would explain the yield difference between the control and the amended plots. In fact, the amounts of nutrients provided by the charcoal were so low (0.225 kg of available N, 2.029 kg of available P, and 4.1 kg of available K) that they could not sustain stable maize grain and straw yields over two consecutive seasons without the addition of *Tithonia*. This shrub would also have created, through its hedges, a microclimate favorable to crops and protected the soil as mulching. Oxalic acid and other organic acids commonly released during *Tithonia* mineralization could improve the phytoavailability of charcoal-supplied N and P, which is often very low [74,75]. Furthermore, without the addition of charcoal, the mineral elements released following the rapid mineralization of *Tithonia* biomass could be subject to various losses. The assumption regarding the synergistic effects is consistent with the findings of previous studies between *Tithonia* or other labile organic matters and charcoals [26,76].

In contrast, the concentrations of N, P, and K in the grains did not differ between T0 and the amended plots (Table 15). Since the accumulation of these three nutrients in the grains is governed by the plant's uptake of N, these results suggest that N uptake in amended plots was not high, despite the large amounts supplied, notably by *Tithonia* biomass. Furthermore, since the accumulation of N

doi:10.20944/preprints202606.1052.v1

and P in the grains has a major influence on yields [77], the low uptake of these nutrients would be one of the factors limiting crop yields [78]. Low N uptake can be explained by a lack of nutrient synchrony between the time of nutrient release and crop nutrient demand or by the dominance of the NH_4^+ form compared to the NO_3^- form. However, maize generally prefers NO_3^- in acidic soils rather than NH_4^+, especially at the seedling stage [26,79]. As for P, its low availability in the soil could be the cause of limited uptake by crops [80]. Furthermore, the N, P, and K concentrations obtained correspond to those reported in the literature in several studies, although the grain yields in those studies were higher than those observed in this study. This suggests that the efficiency of nutrient use, including N, may be low [77].

Thus, the grain yields obtained from amended soils were below the expected yield in SSA, which is in average 4.45 t ha^{-1} [5]. To achieve this, these authors recommend applying 91.0 kg of N, 10.7 kg of P, and 57.1 kg of K ha^{-1}. Thus, considering the results obtained in this study, it would be necessary to increase the quantities of amendments used, primarily *T. diversifolia*, whose main role in this system is to supply nutrients. This is feasible, given the biomass production of *Tithonia* over 16 months (up to 125.56 t ha^{-1} for 16 months). Using this biomass and considering the nutrient recovery rates by maize crops from the mineralization of *Tithonia* (25% for the first crop and 10% for the second) [14], and its chemical composition (N 1.904%, P 0.1639%, K 2.278%), enough nutrients could be provided to crops. Moreover, maize straw can be valorized to provide nutrients or OM [78,81]. Also, it is useful to remedy the low N absorption by maize [82] and increase the planting density from 26,667 in our trial to 53,333 plants ha^{-1} as commonly suggested, and to use varieties with yields around 5 t ha^{-1} and high N-use efficiency [83].

Furthermore, this alley cropping system guarantees the availability of sufficient *Tithonia* biomass for long term fertilization of soils. In fact, sufficient *Tithonia* production is primarily limited by its P nutrition [84]. While the P stock in the 0–30 cm layer in Africa is 1,641 kg ha^{-1} [85] and P exports via *Tithonia* biomass reached up to 205.79 kg ha^{-1} in this study, the hedges would be sustainable for nearly a decade.

5. Conclusions

Maize grain yields are weak and unstable in cases of continuous cultivation in SSA, particularly due to inadequate mineral nutrition. A trial was conducted in Kinshasa to test the effectiveness of charcoal application combined with an agroforestry system based on *Tithonia diversifolia* for increasing maize yields in SSA. The results show that *Tithonia* production in one year was seven times higher than reported in the literature and its biomass was rich in nutrients. Applying *Tithonia* biomass combined with charcoals enabled higher grain yields for amended plots than the control in the first season. However, these yields dropped in the second season, albeit not significantly for the amended plots. These yields were mostly influenced by the maize varieties and quantities of N absorbed. Therefore, prior to implementing this system in SSA, it is necessary to optimize the inputs of N, P and K, targeting the recommended rates (91.0 kg of N, 10.7 kg of P and 57.1 kg of K ha^{-1}) for the optimum yields in SSA (4.45 t ha^{-1}). For this, the following measures should be implemented: planting *Tithonia* at a high density; regular pruning at the height of 50-100 cm; incorporation of biomass in the form of mulch; use of maize varieties whose yield is close to the target; maintenance of the same nutrient provision each season; sowing of maize at a high density; increased availability of N and P for maize crops; and utilization of maize straw as mulch and charcoal. Future works can test various techniques to increase nitrogen absorption and N-use efficiency by maize crops, and the combination of *Tithonia* with low doses of mineral fertilizers and high charcoal rate.

Author Contributions: Conceptualization, J.R.F.N. and J.B.E.D.; methodology, R.S. and J.B.E.D.; software, J.R.F.N.; validation, R.S., J.B.E.D. and E.M.; formal analysis and investigation, J.R.F.N.; resources, J.B.E.D. and E.M.; data curation, R.S.; writing—original draft preparation, J.R.F.N.; writing—review and editing, R.S.; supervision, E.M.; project administration, J.B.E.D; funding acquisition, J.B.E.D and E.M. All authors have read and agreed to the published version of the manuscript.

Funding: Please add: This research was funded by the PASET Regional Scholarship and Innovation Fund.

Data Availability Statement: The original contributions presented in this study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author(s).

Acknowledgments: We gratefully acknowledge the Regional Scholarship and Innovation Fund (RSIF) of the Partnership for Skills in Applied Sciences, Engineering, and Technology (PASET) for providing the scholarship that made this research possible. We also thank the entire Lab for Bioresource Recovery team for granting access to the facilities required for laboratory analyses in Belgium. We extend our thanks to the owner of a farm at Mafumfu (Kinshasa) for providing the land used for the field experiment.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ANOVA	Analysis of variance
Cohex	Cobalt hexamine trichloride
DCB	Dithionite-citrate-bicarbonate
DM	Dry matter
DR.Congo	Democratic republic of Congo
ECEC	Effective cation exchange capacity
IC	Inorganic Carbon
ICP-OES	Inductively Coupled Plasma Optical Emission Spectroscopy
OC	Organic Carbon
OM	Organic matter
SSA	sub-Saharan Africa
TC	Total Carbon

Appendix A. Mineral Exports of *Tithonia diversifolia*

NPK exports by the biomass of *Tithonia diversifolia* were calculated by multiplying the NPK concentrations in the *Tithonia* biomass by the dry biomass quantities obtained for each of the two treatments. The concentrations considered include those of the leaves and stems, and the proportion of each of these organs in the total biomass (1.904% N, 0.1639% P, and 2.278% K). The results are presented in Appendix C.

Appendix D. Mineral exports of *Tithonia diversifolia* from April 2023 to July 2024

Treatments	*Tithonia* Dry biomass (t ha-1)	N exports (kg ha-1)	P exports (kg ha-1)	K exports (kg ha-1)
T1	125.56	2390.66	205.79	2860.25
T2	98.71	1879.43	161.78	2248.61

Appendix B. Potential Nutrient Quantities Available for the Three Successive Maize Crops

These nutrients are assumed to come from both the *Tithonia* biomass and the charcoal. With regard to Tithonia, we took into account the amounts applied during each of the three maize crops (13.15 t ha^{-1}, 5.12 t ha^{-1}, and 9.15 t ha^{-1}, respectively), the nutrient concentrations in the total biomass (1.904% N, 0.1639% P, and 2.278% K), and the nutrient recovery rates by the crops (25% for the first crop and 10% for the second). Thus:

- for the first maize crop, the total amount of nitrogen supplied using *Tithonia* is: 13.15 t ha^{-1} × 1.904% N = 250.376 kg N ha^{-1}.

Since the recovery rate is 25% for the first crop, the amount of available nitrogen is: 25.0376 kg N ha^{-1} × 0.25 = 62.59 kg N ha^{-1}

- the second maize crop is assumed to benefit from 10% of the N supplied by 13.15 t ha^{-1} of Tithonia (25.036 kg N ha^{-1}), and 25% of the N from 5.12 t ha^{-1} of *Tithonia* (24.371 kg N ha^{-1}). The total amount of N that the second maize crop would benefit from is equivalent to 49.4 kg N ha^{-1}.

The results related to the potential nutrients quantities available for maize plants are presented in Appendix E. For the first maize crop, the quantities shown are obtained by summing the inputs of *Tithonia* and charcoals.

Appendix F. Potential nutrient quantities available for the three successive maize crops from *Tithonia* biomass and charcoals

Crops	N supplied (kg ha-1)	P supplied (kg ha-1)	K supplied (kg ha-1)
First maize crop	62.59	7.43	86.28
Second maize crop	49.4	4.21	59.05
Third maize crop	53.25	4.57	63.7

References

1. Landon, R. *Booker Tropical Soil Manual. A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics*; Longman, Booker Take Limed,.; Oxon, UK, 1991;
2. Buresh, R. J., Sánchez, P. A., & Calhoun, F. G; Buresh, R. J., Sánchez, P. A., & Calhoun, F. G. In Proceedings of the Proceedings of an international Symposium cosponsored by divisions A-6 (International agronomy) and S-4 (Soil fertility and plant nutrition), and the international center for research in agroforestry, held at the 88th annual meetings of the American Society of agronomy and the soil science society of America; 1997.
3. Ngongo, M., Ranst, E.V.A.N., Baert, G., Lenge, E.K., Verdoodt, A., Mujinya ,B. B., & Mukalay, J *Guide Des Sols En R.D. Congo. Tome I: Etude et Gestion*; UGent, HoGent, UNILU.; 2009a;
4. Mulaji, C Utilisation Des Composts de Biodéchets Ménagers Pour l'amélioration de La Fertilité Des Sols Acides de La Province de Kinshasa (République Démocratique Du Congo), Université de Liège-Gembloux Agro-Bio Tech: Belgique, 2011.
5. Ten Berge, H.F.M.; Hijbeek, R.; Van Loon, M.P.; Rurinda, J.; Tesfaye, K.; Zingore, S.; Craufurd, P.; Van Heerwaarden, J.; Brentrup, F.; Schröder, J.J.; et al. Maize Crop Nutrient Input Requirements for Food Security in Sub-Saharan Africa. *Global Food Security* **2019**, *23*, 9–21, doi:10.1016/j.gfs.2019.02.001.
6. Yang, L.; Wu, Y.; Wang, Y.; An, W.; Jin, J.; Sun, K.; Wang, X. Effects of Biochar Addition on the Abundance, Speciation, Availability, and Leaching Loss of Soil Phosphorus. *Science of The Total Environment* **2021**, *758*, 143657, doi:10.1016/j.scitotenv.2020.143657.
7. He, X.; Augusto, L.; Goll, D.S.; Ringeval, B.; Wang, Y.; Helfenstein, J.; Huang, Y.; Yu, K.; Wang, Z.; Yang, Y.; et al. Supplementary Material to "Global Patterns and Drivers of Soil Total Phosphorus Concentration" 2021.
8. Agegnehu, G.; Amede, T.; Erkossa, T.; Yirga, C.; Henry, C.; Tyler, R.; Nosworthy, M.G.; Beyene, S.; Sileshi, G.W. Extent and Management of Acid Soils for Sustainable Crop Production System in the Tropical Agroecosystems: A Review. *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science* **2021**, *71*, 852–869, doi:10.1080/09064710.2021.1954239.
9. Oyebiyi, O.O. Distribution and Forms of Iron and Aluminium Oxides in Tropical Soils of Central Southwestern Nigeria. *Environ Earth Sci* **2024**, *83*, 95, doi:10.1007/s12665-024-11420-9.
10. Liniger, H.P., Studer, R.M., Hauert, C., & Gurtner, M *La Pratique de La Gestion Durable Des Terres. Directives et Bonnes Pratiques En Afrique Subsaharienne*; TerrAfrica, Panorama mondial des approches et technologies de conservation (WOCAT) et Organisation des Nations Unies pour l'alimentation et l'agriculture (FAO).; 2011;
11. Yemadje, P.L.; Amonmidé, I.; Loison, R.; Crétenet, M.; Koussihouede, H.; Atakoun, A.M.; Fujisaki, K.; Dogliotti, S.; Sekloka, E.; Letourmy, P.; et al. Regenerating Productivity after Soil Fertility Depletion in a 20-Year Cotton–Maize Rotation in Benin. *Nutr Cycl Agroecosyst* **2025**, *131*, 253–270, doi:10.1007/s10705-025-10429-1.

12. Jama, B.; Palm, C.A.; Buresh, R.J.; Niang, A.; Gachengo, C.; Nziguheba, G.; Amadalo, B. Tithonia Diversifolia as a Green Manure for Soil Fertility Improvement in Western Kenya: A Review. *Agroforestry Systems* **2000**, *49*, 201–221, doi:10.1023/A:1006339025728.
13. Glaser, B.; Lehmann, J.; Zech, W. Ameliorating Physical and Chemical Properties of Highly Weathered Soils in the Tropics with Charcoal - a Review. *Biology and Fertility of Soils* **2002**, *35*, 219–230, doi:10.1007/s00374-002-0466-4.
14. Graves, A., Matthews, R., Waldie, K., Bhurtel, R., & Quashie-Sam, J *Review of Technologies Being Evaluated for the Forest/Agriculture Interface. Final Report Submitted to the UK Department for International Development's (DFID) Natural Resources Systems Programme (NRSP) to Fulfil Requirements under the Research Contract R7560*; Institute of Water and Environment, Cranfield University, 2011; p. 229;.
15. Mucheru-Muna, M.; Mugendi, D.; Pypers, P.; Mugwe, J.; Kung'U, J.; Vanlauwe, B.; Merckx, R. ENHANCING MAIZE PRODUCTIVITY AND PROFITABILITY USING ORGANIC INPUTS AND MINERAL FERTILIZER IN CENTRAL KENYA SMALL-HOLD FARMS. *Ex. Agric.* **2014**, *50*, 250–269, doi:10.1017/S0014479713000525.
16. Kätterer, T.; Roobroeck, D.; Kimutai, G.; Karltun, E.; Nyberg, G.; Sundberg, C.; De Nowina, K.R. Maize Grain Yield Responses to Realistic Biochar Application Rates on Smallholder Farms in Kenya. *Agron. Sustain. Dev.* **2022**, *42*, 63, doi:10.1007/s13593-022-00793-5.
17. Stavi, I.; Lal, R. Agroforestry and Biochar to Offset Climate Change: A Review. *Agron. Sustain. Dev.* **2013**, *33*, 81–96, doi:10.1007/s13593-012-0081-1.
18. Singh, R.; Kumari, T.; Verma, P.; Singh, B.P.; Raghubanshi, A.S. Compatible Package-Based Agriculture Systems: An Urgent Need for Agro-Ecological Balance and Climate Change Adaptation. *Soil Ecol. Lett.* **2022**, *4*, 187–212, doi:10.1007/s42832-021-0087-1.
19. Fungo, B.; Lehmann, J.; Kalbitz, K.; Tenywa, M.; Thionġo, M.; Neufeldt, H. Emissions Intensity and Carbon Stocks of a Tropical Ultisol after Amendment with Tithonia Green Manure, Urea and Biochar. *Field Crops Research* **2017**, *209*, 179–188, doi:10.1016/j.fcr.2017.05.013.
20. Obiakara, M.C.; Fourcade, Y. Climatic Niche and Potential Distribution of Tithonia Diversifolia (Hemsl.) A. Gray in Africa. *PLoS ONE* **2018**, *13*, e0202421, doi:10.1371/journal.pone.0202421.
21. Opala, P.A. Recent Advances in the Use of Tithonia Diversifolia Green Manure for Soil Fertility Management in Africa: A Review. *AG* **2020**, *41*, doi:10.18805/ag.R-141.
22. Arif, M.; Ali, S.; Ilyas, M.; Riaz, M.; Akhtar, K.; Ali, K.; Adnan, M.; Fahad, S.; Khan, I.; Shah, S.; et al. Enhancing Phosphorus Availability, Soil Organic Carbon, Maize Productivity and Farm Profitability through Biochar and Organic–Inorganic Fertilizers in an Irrigated Maize Agroecosystem under Semi-arid Climate. *Soil Use and Management* **2021**, *37*, 104–119, doi:10.1111/sum.12661.
23. Kriticos, J.M.; Kriticos, D.J. Pretty (and) Invasive: The Potential Global Distribution of *Tithonia Diversifolia* under Current and Future Climates. *Invasive plant sci. manag.* **2021**, *14*, 205–213, doi:10.1017/inp.2021.29.
24. Ashraf, S.M.K.; Ripta, S.K.; Rana, M.T.; Islam, K.K. Biochar Enhanced Agroforestry Systems for Carbon Sequestration, Soil Health and Climate Resilience. *Discov. For.* **2025**, *1*, 53, doi:10.1007/s44415-025-00057-6.
25. Spokas, K.A.; Cantrell, K.B.; Novak, J.M.; Archer, D.W.; Ippolito, J.A.; Collins, H.P.; Boateng, A.A.; Lima, I.M.; Lamb, M.C.; McAloon, A.J.; et al. Biochar: A Synthesis of Its Agronomic Impact beyond Carbon Sequestration. *J. Environ. Qual.* **2012**, *41*, 973–989, doi:10.2134/jeq2011.0069.
26. Partey, S.T.; Preziosi, R.F.; Robson, G.D. Short-Term Interactive Effects of Biochar, Green Manure, and Inorganic Fertilizer on Soil Properties and Agronomic Characteristics of Maize. *Agric Res* **2014**, *3*, 128–136, doi:10.1007/s40003-014-0102-1.
27. Manolikaki, I.; Diamadopoulos, E. Positive Effects of Biochar and Biochar-Compost on Maize Growth and Nutrient Availability in Two Agricultural Soils. *Communications in Soil Science and Plant Analysis* **2019**, *50*, 512–526, doi:10.1080/00103624.2019.1566468.
28. Frimpong, K.A.; Phares, C.A.; Boateng, I.; Abban-Baidoo, E.; Apuri, L. One-Time Application of Biochar Influenced Crop Yield across Three Cropping Cycles on Tropical Sandy Loam Soil in Ghana. *Heliyon* **2021**, *7*, e06267, doi:10.1016/j.heliyon.2021.e06267.

29. Zhao, H.; Xie, T.; Xiao, H.; Gao, M. Biochar-Based Fertilizer Improved Crop Yields and N Utilization Efficiency in a Maize–Chinese Cabbage Rotation System. *Agriculture* **2022**, *12*, 1030, doi:10.3390/agriculture12071030.
30. Kobayashi, K. Factors Affecting Phytotoxic Activity of Allelochemicals in Soil. *Weed Biology and Management* **2004**, *4*, 1–7, doi:10.1111/j.1445-6664.2003.00112.x.
31. Partey, S.T The Agronomic Qualities of the Mexican Sunflower (Tithonia Diversifolia) for Soil Fertility Improvement in Ghana: An Exploratory Study. Doctorate, Kwame Nkrumah University of Science and Technology, 2010.
32. Agbede, T.M.; Adekiya, A.O.; Ogeh, J.S. Response of Soil Properties and Yam Yield to *Chromolaena Odorata* (Asteraceae) and *Tithonia Diversifolia* (Asteraceae) Mulches. *Archives of Agronomy and Soil Science* **2014**, *60*, 209–224, doi:10.1080/03650340.2013.780127.
33. Otusanya, O.O., Ogunwole, A. A., & Tijani, M.O Allelopathic Effect of Tithonia Diversifolia and Chromolaena Odorata on the Germination, Growth and Chlorophyll Accumulation of Hibiscus Sabdariffa (L.) 2015, *5*, 1–14.
34. George, T.S.; Gregory, P.J.; Wood, M.; Read, D.; Buresh, R.J. Phosphatase Activity and Organic Acids in the Rhizosphere of Potential Agroforestry Species and Maize. *Soil Biology and Biochemistry* **2002**, *34*, 1487–1494, doi:10.1016/S0038-0717(02)00093-7.
35. Yuan, Q.; Gao, Y.; Ma, G.; Wu, H.; Li, Q.; Zhang, Y.; Liu, S.; Jie, X.; Zhang, D.; Wang, D. The Long-Term Effect of Biochar Amendment on Soil Biochemistry and Phosphorus Availability of Calcareous Soils. *Agriculture* **2025**, *15*, 458, doi:10.3390/agriculture15050458.
36. Makanzu, F Etude de l'érosion Ravinante à Kinshasa : Dynamisme Pluvio-Morphogénique et Développement d'un Outil de Prévision. Doctorat, Université de Kinshasa (RD.Congo), 2014.
37. Kasongo, R.K.; Van Ranst, E.; Verdoodt, A.; Kanyankagote, P.; Baert, G. Impact of *Acacia Auriculiformis* on the Chemical Fertility of Sandy Soils on the Batéké Plateau, D.R. Congo. *Soil Use and Management* **2009**, *25*, 21–27, doi:10.1111/j.1475-2743.2008.00188.x.
38. Koy, R. Amélioration de La Qualité Des Sols Sableux Du Plateau Des Batéké (RD Congo) Par Application Des Matériels Géologiques et Des Déchets Organiques Industriels Locaux. Doctorat, Gent (Belgique), 2010.
39. Chalker-Scott, L. Impact of Mulches on Landscape Plants and the Environment — A Review. *Journal of Environmental Horticulture* **2007**, *25*, 239–249, doi:10.24266/0738-2898-25.4.239.
40. Vyamana, V.G.; Chamshama, S.A.O.; Andrew, S.M. Soil Nutrients and Maize Yields Responses to Indigenous Agroforestry Tree Post-Fallows Management in Tanzania. *Trees, Forests and People* **2021**, *6*, 100164, doi:10.1016/j.tfp.2021.100164.
41. Partey, S.T. Effect of Pruning Frequency and Pruning Height on the Biomass Production of Tithonia Diversifolia (Hemsl) A. Gray. *Agroforest Syst* **2011**, *83*, 181–187, doi:10.1007/s10457-010-9367-y.
42. Senarathne, S.H.S.; Atapattu, A.J.; Raveendra, T.; Mensah, S.; Dassanayake, K.B. Biomass Allocation and Growth Performance of Tithonia Diversifolia (Hemsl.) A. Gray in Coconut Plantations in Sri Lanka. *Agroforest Syst* **2019**, *93*, 1865–1875, doi:10.1007/s10457-018-0290-y.
43. Whitman, T.; Nicholson, C.F.; Torres, D.; Lehmann, J. Climate Change Impact of Biochar Cook Stoves in Western Kenyan Farm Households: System Dynamics Model Analysis. *Environ. Sci. Technol.* **2011**, *45*, 3687–3694, doi:10.1021/es103301k.
44. Joseph, S.; Graber, E.; Chia, C.; Munroe, P.; Donne, S.; Thomas, T.; Nielsen, S.; Marjo, C.; Rutlidge, H.; Pan, G.; et al. Shifting Paradigms: Development of High-Efficiency Biochar Fertilizers Based on Nano-Structures and Soluble Components. *Carbon Management* **2013**, *4*, 323–343, doi:10.4155/cmt.13.23.
45. Lehmann, J., Jda Silva, P., Rondon, M., da Silva, C.M., Greenwood, J., Nehls, T., Steiner, C. & Glaser B. "Slash-and-Char: A Feasible Alternative for Soil Fertility Management in the Central Amazon?"; Thailand, 2002.
46. Dubiez, E., Péroches, A., Akalakou, M.C., & Gazull L. *Rapport d'étude Sur l'organisation de La Filière Bois-Énergie de La Ville de Kinshasa*; CAFI, FONAREDD, PNUD, 2021; p. 84;.
47. FAO *Standard Operating Procedure for Quasi Total Elements in Soil by Acid Digestion, Including Heavy Metals*; Rome, 2023a;

48. Karasakal, A. Determination of Major, Minor, and Toxic Elements in Tropical Fruits by ICP-OES After Different Microwave Acid Digestion Methods. *Food Anal. Methods* **2021**, *14*, 344–360, doi:10.1007/s12161-020-01884-3.
49. Da Silva, I.J.S.; Da Silva, M.M.; Da Silva, R.G.M.F.; De França, E.J.; Da Silva, M.J.; Kato, M.T. Microwave-Assisted Digestion for Multi-Elemental Determination in Beans, Basil, and Mint by ICP OES and Flame Photometry: An Eco-Friendly Alternative. *Food Chemistry* **2025**, *481*, 143970, doi:10.1016/j.foodchem.2025.143970.
50. Dhaliwal, G.S.; Gupta, N.; Kukal, S.S.; Kaur, M. Standardization of Automated Vario EL III CHNS Analyzer for Total Carbon and Nitrogen Determination in Soils. *Communications in Soil Science and Plant Analysis* **2011**, *42*, 971–979, doi:10.1080/00103624.2011.558965.
51. Gautam, V.P.; Mishra, S.; Ahmed, H. Comparison of Total Nitrogen Estimation by Kjeldahl Method and CHNS Analyzer in Dry Tropical Grassland. *IJPE* **2023**, *9*, 180–182, doi:10.18811/ijpen.v9i02.13.
52. Singh, B., Camps-Arbestain M., & Lehmann J. (Eds) *Biochar: A Guide to Analytical Methods*; CRC Press/Taylor and Francis Group: Bica Raton, London, New-York, 2017;
53. Nel, T.; Bruneel, Y.; Smolders, E. Comparison of Five Methods to Determine the Cation Exchange Capacity of Soil. *J. Plant Nutr. Soil Sci.* **2023**, *186*, 311–320, doi:10.1002/jpln.202200378.
54. FAO *Standard Operating Procedure for Soil Available Phosphorus, Bray I and Bray II Method*; Rome, 2021;
55. Wanke, D.J.; Heichel, J.; Zikeli, S.; Müller, T.; Hartmann, T.E. Comparison of Soil Phosphorus Extraction Methods Regarding Their Suitability for Organic Farming Systems. *J. Plant Nutr. Soil Sci.* **2023**, *186*, 599–608, doi:10.1002/jpln.202300129.
56. Xue, B.; Huang, L.; Huang, Y.; Zhou, F.; Li, F.; Kubar, K.A.; Li, X.; Lu, J.; Zhu, J. Roles of Soil Organic Carbon and Iron Oxides on Aggregate Formation and Stability in Two Paddy Soils. *Soil and Tillage Research* **2019**, *187*, 161–171, doi:10.1016/j.still.2018.12.010.
57. Beverwijk, A. Particle Size Analysis of Soils by Means of the Hydrometer Method. *Sedimentary Geology* **1967**, *1*, 403–406, doi:10.1016/0037-0738(67)90070-X.
58. Weber, B.; Stadlbauer, E.A.; Schlich, E.; Eichenauer, S.; Kern, J.; Steffens, D. Phosphorus Bioavailability of Biochars Produced by Thermo-chemical Conversion. *Z. Pflanzenernähr. Bodenk.* **2014**, *177*, 84–90, doi:10.1002/jpln.201300281.
59. Jindo, K.; Audette, Y.; Higashikawa, F.S.; Silva, C.A.; Akashi, K.; Mastrolonardo, G.; Sánchez-Monedero, M.A.; Mondini, C. Role of Biochar in Promoting Circular Economy in the Agriculture Sector. Part 1: A Review of the Biochar Roles in Soil N, P and K Cycles. *Chem. Biol. Technol. Agric.* **2020**, *7*, 15, doi:10.1186/s40538-020-00182-8.
60. Nyami, B.L.; Sudi, C.K.; Lejoly, J. Effet du biochar et des feuilles de Tithonia diversifolia combiné à l'engrais minéral sur la culture du maïs (Zea mays L.) et les propriétés d'un sol ferralitique à Kinshasa (RDC). *Biotechnol. Agron. Soc. Environ.* **2016**, 57–67, doi:10.25518/1780-4507.12592.
61. Nziguheba, G., & Bünemann, E.K. *11. Organic Phosphorus Dynamics in Tropical Agroecosystems*; Organic Phosphorus in the Environment; Turner, B.L., Frossard, E., Baldwin, D.S.; CAB International, 2005;
62. Sollins, P.; Robertson, G.P.; Uehara, G. Nutrient Mobility in Variable- and Permanent-Charge Soils. *Biogeochemistry* **1988**, *6*, 181–199, doi:10.1007/BF02182995.
63. Ferraz-Almeida, R. Balance of Nitrate and Ammonium in Tropical Soil Conditions: Soil Factors Analyzed by Machine Learning. *Nitrogen* **2024**, *5*, 732–745, doi:10.3390/nitrogen5030048.
64. Vargas Velázquez, V.T.; Pérez Hernández, P.; López Ortiz, S.; Castillo Gallegos, E.; Cruz Lazo, C.; Jarillo Rodríguez, J. Producción y Calidad Nutritiva de Tithonia Diversifolia (Hemsl.) A. Grey En Tres Épocas Del Año y Su Efecto En La Preferencia Por Ovinos Pelibuey. *Rev. Mex. Cienc. Pecu.* **2022**, *13*, 240–257, doi:10.22319/rmcp.v13i1.5906.
65. Nuwarapaksha, T.D.; Dissanayake, W.K.; Gunathilaka, W.S.; Udumann, S.S.; Dissanayaka, N.S.; Atapattu, A.J. Assessing the Optimum Harvesting Stage of Tithonia Diversifolia as Climate Smart Soil Amendment for Coconut Plantations. In Proceedings of the The 2nd International Online Conference on Agriculture; MDPI, November 10 2023; p. 1.

66. Ma, S.; He, F.; Tian, D.; Zou, D.; Yan, Z.; Yang, Y.; Zhou, T.; Huang, K.; Shen, H.; Fang, J. Variations and Determinants of Carbon Content in Plants: A Global Synthesis. *Biogeosciences* **2018**, *15*, 693–702, doi:10.5194/bg-15-693-2018.
67. Brown, P. Phloem Mobility of Boron Is Species Dependent: Evidence for Phloem Mobility in Sorbitol-Rich Species. *Annals of Botany* **1996**, *77*, 497–506, doi:10.1006/anbo.1996.0060.
68. Brown, P.H.; Shelp, B.J. Boron Mobility in Plants. In *Boron in Soils and Plants: Reviews*; Dell, B., Brown, P.H., Bell, R.W., Eds.; Springer Netherlands: Dordrecht, 1997; pp. 85–101 ISBN 978-94-010-6352-4.
69. WBC World Biochar Certificate – Guidelines for a Sustainable Production of Biochar and Its Certification 2023.
70. Garcia, B.; Alves, O.; Rijo, B.; Lourinho, G.; Nobre, C. Biochar: Production, Applications, and Market Prospects in Portugal. *Environments* **2022**, *9*, 95, doi:10.3390/environments9080095.
71. Yulnafatmawita Y., Aprisal A. & Hakim N. Role of Alley Cropping System with Cultivated Tithonia (Tithonia Diversifolia) on Soil Erosion and Soybean (Glycine Max Merr L) Production at Ultisol under Wet Tropical Area 2017, *8*, 1237–1248.
72. Sopha, G.A.; Hermanto, C.; Kerckhoffs, H.; Heyes, J.A.; Hanly, J. Response of Selected Chemical Properties of Extremely Acidic Soils on the Application of Limes, Rice Husk Biochar and Zeolite. *J.Degrade.Min.Land Manage.* **2022**, *10*, 4011, doi:10.15243/jdmlm.2022.101.4011.
73. Ghodszad, L.; Reyhanitabar, A.; Oustan, S.; Alidokht, L. Phosphorus Sorption and Desorption Characteristics of Soils as Affected by Biochar. *Soil and Tillage Research* **2022**, *216*, 105251, doi:10.1016/j.still.2021.105251.
74. Ikerra, S.T.; Semu, E.; Mrema, J.P. The ‘Secret’ Behind the Good Performance of Tithonia Diversifolia on P Availability as Compared to Other Green Manures. In *Innovations as Key to the Green Revolution in Africa*; Bationo, A., Waswa, B., Okeyo, J.M., Maina, F., Kihara, J.M., Eds.; Springer Netherlands: Dordrecht, 2011; pp. 235–243 ISBN 978-90-481-2541-8.
75. IPCC Summary for Policymakers. In *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*; 2019.
76. Abdul-Aziz, A.-L.; Abukari, I.A.; Galadima, M.M.; Haruna, A.; Abubakari, M.; Abdulai, R. Biochar Effects on Soil Properties and Yield of Maize in Northern Region, Ghana. *Discov Agric* **2025**, *3*, 103, doi:10.1007/s44279-025-00271-y.
77. Singh, R.; Sawatzky, S.K.; Thomas, M.; Akin, S.; Zhang, H.; Raun, W.; Arnall, D.B. Nitrogen, Phosphorus, and Potassium Uptake in Rain-Fed Corn as Affected by NPK Fertilization. *Agronomy* **2023**, *13*, 1913, doi:10.3390/agronomy13071913.
78. Zeng, X-l., Zhang, Q., Liu, Z-x., & Dai, S-y Difference of Maize Straw-to-Grain Ratio under Different Production Environments Based on Meta-Analysis 2025, *46*, 1708–1721.
79. Zhang, H.-Q.; Shen, R.-F.; Zhao, X.-Q. Nitrogen Source Preference in Maize at Seedling Stage Is Mainly Dependent on Growth Medium pH. *Agronomy* **2022**, *12*, 2149, doi:10.3390/agronomy12092149.
80. Oyebanjo, O.; Ekosse, G.-I.; Odiyo, J. Phosphorus Sorption in Soils and Clay Fractions Developed from Different Parent Rocks in Limpopo Province, South Africa. *Sustainability* **2022**, *14*, 8528, doi:10.3390/su14148528.
81. Yang, H.; Li, J.; Wu, G.; Huang, X.; Fan, G. Maize Straw Mulching with No-Tillage Increases Fertile Spike and Grain Yield of Dryland Wheat by Regulating Root-Soil Interaction and Nitrogen Nutrition. *Soil and Tillage Research* **2023**, *228*, 105652, doi:10.1016/j.still.2023.105652.
82. Ordóñez, R.A.; Olmedo-Pico, L.; Ferela, A.; Trifunovic, S.; Eudy, D.; Archontoulis, S.; Vyn, T.J. Modern Maize Hybrids Have Increased Grain Yield and Efficiency Tolerances to Nitrogen-Limited Conditions. *European Journal of Agronomy* **2025**, *168*, 127621, doi:10.1016/j.eja.2025.127621.
83. Arisede, C.; Mainassara, Z.-A.; Jill, C.; Amsal, T.; Cosmos, M.; Bish, D.; Benhildah, M.; Mike, O.; Maruthi, P.B. Low-N Stress Tolerant Maize Hybrids Have Higher Fertilizer N Recovery Efficiency and Reduced N-Dilution in the Grain Compared to Susceptible Hybrids under Low N Conditions. *Plant Production Science* **2020**, *23*, 417–426, doi:10.1080/1343943X.2020.1746188.

doi:10.20944/preprints202606.1052.v1

84. Adesina, A.A., Coulibaly, D., Manyong, V.M., Sanginga, P.C., Mbila, D., Chianu J., & Kamleu G Policy Shifts and Adoption of Alley Farming in West and Central Africa 1999.
85. He, Y.T.; He, X.H.; Xu, M.G.; Zhang, W.J.; Yang, X.Y.; Huang, S.M. Long-Term Fertilization Increases Soil Organic Carbon and Alters Its Chemical Composition in Three Wheat-Maize Cropping Sites across Central and South China. *Soil and Tillage Research* **2018**, *177*, 79–87, doi:10.1016/j.still.2017.11.018.