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Biochar Improves Maize Nutritional Status and Yield under Two Soil Tillage Modes

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Abstract: ***Our field trial in Cameroon assessed the effect of biochar on nutrient uptake and maize yield, following a single application of 15 t ha^{-1} of biochar to an oxisol under two soil tillage modes. Treatments were (T2) fertilizer + corncob biochar (CCB); (T3) fertilizer + eucalyptus biochar (EB); (T4) Straw + fertilizer + CCB; (T5) Straw + fertilizer + EB and the control treatment (T1) consisted of fertilizer + straw only. Maize leaf tissues were collected at tasselling during each production period and analysed for macro-elements. Biochar significantly increased maize yield by 55% above control during the first production period and by 54 % during the second period. The CCB amendment positively interacted with the furrows and ridges (FR) tillage mode to improve yield during the first production period. By compositional nutritional diagnosis (CND), the most deficient nutrients were identified as P, Mg and K. Despite higher yield, maize plants in biochar-treated plots were more nutritionally unbalanced during the first production period compared to control plants; the inverse was observed during the second production period. Further studies are required to improve maize fertilisation recommendations and to refine application frequency of biochar for continuous maize production on oxisols.***

Keywords: Oxisol, compositional nutrient diagnosis, biochar, plant nutrition, maize production

1. Introduction

One of the environmental challenges for many tropical countries is to limit deforestation while increasing food production [1]. Oxisols, predominant in the tropics, contain kaolinitic clay minerals and clay-sized oxides and hydroxides of metals such as iron and aluminium, few weatherable minerals, high levels of secondary minerals, low pH, deep profiles and high levels of available aluminium [2]. Most of these properties contribute to reducing their capacities to retain plant nutrients. Over the past 10 years, there have been numerous studies of biochar application, which help to determine appropriate methods for biochar use to promote sustainable agriculture [3]. However, few studies have assessed the impact of biochar on maize production under different tillage modes. The interaction of biochar amendment with the furrow and ridges system, commonly applied by small farm holders to control erosion, potentially offers an opportunity to improve biochar use efficiency, since the biochar is concentrated spatially where most of the plant roots are located (in the ridge).

In order to better interpret the responses of maize to biochar amendment under different tillage modes, foliar analysis of the crop can be used as a diagnostic tool to detect nutrient deficiencies [4,5]. Compositional nutrient diagnostic (CND) is often used as an aid to assess the nutrient status of maize agro-ecosystems [6]. In fact, plant leaf nutrient composition is a unique consequence of plant adaptation to a particular nutrient environment under a given set of limiting factors [7]. Stress, resulting in growth disturbance, is related not only to deficiency of a particular nutrient, but also to inadequate relations among nutrients [8]. Prior experiments with biochar materials from bio-wastes have reported increased soil nutrient availability in highly weathered tropical soils and short-term increases in crop growth [9]. For instance, [10]reported an increased uptake of P, K, Ca, Zn, and Cu by cowpea (*Vigna unguiculata* (L.)Walp.) and rice (*Oryza sativa* L.) with higher charcoal additions on ferralsol and anthrosol soils. [11] successfully used leaf foliar analysis to identify Ca and Mg as deficient nutrients in a Columbian oxisol after biochar application.

The present study assesses the effect of two locally-produced biochars on maize nutrient uptake and yield under two common soil tillage modes. We hypothesized that the application of biochar at 15 t ha^{-1} will: (i) improve maize yield during the first two production periods; (ii) result in a better nutritional status of plants in plots with biochar amendment.

2. Materials and methods

2.1 Biochar properties and establishment of field experiment

Two types of biochars were produced from local organic residues, eucalyptus tree bark (EB) and corncob (CCB), using the same pyrolysis process, a retort kiln at a temperature of 300°C, with average residence time of four hrs and gas recycling. These biochars were characterized in a previous study by [12]. Some of the main properties of the chars, apart from those presented in Table 1, included alkaline pH (9.3 for CCB; 8.1 for EB) and relatively high ash content (10.1 % for EB; 5.3 % for CCB). The field trial was carried out from December 2014 to December 2015, in an agricultural farm in the western highlands of Cameroon in Central Africa (5°36'52'' N, 10°16'85'' E) at 1418 m altitude, with 5% slope. The plot was under fallow three years prior to the experiment. The soil is a clay loam with a pH of 4.9 and a low bulk density of 0.76 g cm^{-3}[12]. The climate is tropical wet with a mean annual rainfall of 1850 mm, principally over 8 months from March to October, and mean maximum and minimum temperatures of 29.4°C and 12.9 °C.

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Table 1: Equivalent rate for biochar nutrient and carbon supply, maize needs and recommended fertilizer application rate

Parameter	*Units*	*CCB* (applied at 15 t ha^{-1})*	*EB* (applied at 15 t ha^{-1})*	*Recommended local mineral fertilization (200kg ha^{-1} NPK + 100 kg ha^{-1} N)*	*Maize needs for 6 t ha^{-1} yield***	*Maize needs for 3 t ha^{-1}yield***
Nitrogen	kg ha^{-1}	132	71	86	120	72
Phosphorus	kg ha^{-1}	27	25	9	22	16
Potassium	kg ha^{-1}	155	44	17	20	45
Calcium	kg ha^{-1}	5	86	/	24	/
Magnesium	kg ha^{-1}	5	6	/	25	/
Sodium	kg ha^{-1}	3	6	/	15	5
Organic Carbon	kg ha^{-1}	4455	4170	/	/	/

*Adapted from [12]**Adapted from[13].

An irrigation system was designed and installed to ensure adequate soil moisture during the experimental period. The irrigation regime was based on basic infiltration rate of the soil estimated at 2.50x10^{-4} m.s^{-1} using the double ring infiltrometer method [14], corn water requirements as per growing stages [15], actual evapotranspiration and estimated soil water retention capacity. Water was pumped from a river to irrigate the plots using sprinklers twice weekly during the dry season (first production period, from January to May 2014) and occasionally according to rain events during the rainy season (second production period, from July to November 2014). The experimental design was a split-plot with the main plots being the soil tillage mode (flat vs furrows and ridges system), and the sub-plots being one of the five treatments (T1-T5). Individual plot size measured 16 m^2, spaced every 0.8 m. Three blocks set perpendicularly to the slope gradient were used as three replicates. The control treatment included fertilizer and the incorporation of straw, without biochar (T1). Fertilization consisted in manual application of N-P-K (20-10-10) at the rate of 200 t ha^{-1} and urea (46-0-0) at 100 t ha^{-1}, which is a standard rate for local producers. The treated plots received fertilizer and CCB (T2); fertilizer and EB (T3); fertilizer, CCB and straw (T4); and fertilizer, EB and straw (T5). Both biochars were manually applied at a rate of 15 t ha^{-1} (dry weight). This followed suggested application rates in the literature [16]. The land was tilled using a rotor cultivator for flat plots (FP) and a hoe for furrow and ridges plots (FR). Biochars without straw (T2 and T3) and with straw (T4 and T5) were buried at 15 cm depth using a hoe in ridges and a rotor cultivator in FP. Each FR had 3 ridges of 1 m each spaced 50 cm apart. Straw originated from grasses during fallow.

Improved corn seeds (PANNAR 12^{TM}) were sown manually at about 4 cm depth at a density of 4 plant m^{-2} (50 cm x 60 cm in ridges and 50 cm x 65 cm in FP). After harvesting (5 months later), the agricultural residues were removed from the field and plots were again ploughed using the hoe for ridges and the rotor cultivator for flat surfaces. Ridges were not moved to form new ones but rather disturbed and remade at the same location. A second corn production period of five months was then completed on the same plots, without application of either fertilizer or biochars. Weeding was done manually twice per production period and earthing up once during the second weeding. Plants were chemically treated once per production period as per standard method of farmers in the region, using Cypercal C720 EC^{TM} (active component cypermethrine) to control caterpillars. This attack was not specific to a particular plot.

2.2 Yield estimation, leaf sampling and analysis

Maize ears were manually harvested from all plants in rows number 2, 4 and 6 for FP and 2, 4 and 5 for FR, to avoid edge effects. Ears were shelled by hand then weighed, dried in an oven at 60°C for 72 h, then weighed again. These data were used to estimate moisture content on a dry weight basis. Twenty-four maize plants were harvested from each plot, which is equivalent to a surface area of 6 m^2 given the density of 4 plants per m^2. Grain yield was estimated as the ratio of dried maize grain over a surface area and conversion was done to obtain the final yield in t ha^{-1}. Ten topmost fully-developed leaf samples were randomly clipped at their base at tasselling [17] from ten healthy plants distributed throughout each plot, during the first and second production period. Leaves were then dried at 60°C, weighed, and finely ground. The obtained powder was acid digested, analysed for N content using CNS-LECO Trumac, then for P, K, Ca, and Mg contents using the ICP-OES Optima 4300DV (Perkin-Elmer instrument).

2.3 Statistical analyses

The effect of treatments on leaf chemical parameters were analysed using the GLIMIX procedure of SAS followed by the Tukey HSD test for multiple comparisons. Analyses were completed in two phases. First, the treatments T2, T3, T4, and T5 were compared to the control (T1) for the response variables (N, P, K, Ca, Mg and yield). Second, the treatments were compared to test the effect of biochar type, soil tillage mode, production period and presence or absence of straw. The compositional nutrient diagnosis of plant leaves (CND) was computed using the procedure outlined by [18]. The theoretical basis of the CND method is that plants with balanced foliar nutrition (i.e., CND-r^2 close to zero) will have a greater biomass and yield than plants with a foliar nutrient imbalance [19,20]. The full composition array of nutrient proportions in plant leaves forms a simplex (S_d) made of d + 1 nutrient proportions including d measured nutrients and a filling value (Rd) to sum up the dry matter concentration (%) to 100. It is defined as follows (d=5, in this case):

$$S_d = [(\mathrm{N, P, K, Ca, Mg,}\ R_d) : N > 0;\ P > 0;\ K > 0;\ Ca > 0;\ Mg > 0;\ Rd > 0;\ \mathrm{N + P + K + Ca + Mg + Rd} = 100] \quad (1)$$

Where Rd was computed as follows:

$$R_d = 100 - (\mathrm{N + P + K + Ca + Mg}) \quad (2)$$

The nutrient proportions were considered scale invariant after dividing by the geometric mean (G) of the d+1 components [19] as follows

$$G = [\mathrm{N\ x\ P\ x\ K\ x\ Ca\ x\ Mg\ x}\ R_d]^{\frac{1}{d+1}} \quad (3)$$

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Row-centered log ratios (clr) for each nutrient was computed as follows:

$$\mathrm{V_N} = \ln\left(\frac{\mathrm{N}}{\mathrm{G}}\right);\ \mathrm{V_P} = \ln\left(\frac{\mathrm{P}}{\mathrm{G}}\right);\ \mathrm{V_K} = \ln\left(\frac{\mathrm{K}}{\mathrm{G}}\right);\ \mathrm{V_{Ca}} = \ln\left(\frac{\mathrm{Ca}}{\mathrm{G}}\right);\ \mathrm{V_{Mg}} = \ln\left(\frac{\mathrm{Mg}}{\mathrm{G}}\right);$$

$$\mathrm{V_{R_d}} = \ln\left(\frac{\mathrm{R_d}}{\mathrm{G}}\right) \text{ and } \mathrm{V_N} + \mathrm{V_P} + \mathrm{V_k} + \mathrm{V_{Ca}} + \mathrm{V_{Mg}} + \mathrm{V_{Rd}} = 0 \qquad (4)$$

The observations were ranked in decreasing yield order, and a partition of the database between two sub-populations was iterated using the Cate-Nelson procedure [21,22]. The highest acceptable yield cut-off value across nutrient expressions was selected to ascertain that the minimum yield target for a high-yield subpopulation will be classified as high yield, regardless of the nutrition expression [4]. The CND norms $\mathbf{V_i^*}$ and their corresponding standard deviation $\boldsymbol{S_i^*}$were calculated as the means and standard deviation values of row-centered log ratios $\mathbf{v_i}$ of the high-yield specimens, where i= (N, P, K, Ca, Mg, $\mathrm{R_d}$). The CND indexes (nutrient disequilibrium indexes) noted $\mathbf{I_i}$ as for the ith nutrient and the global nutrient disequilibrium index (CND-r^2) were computed as a standard variable using the CND norms $\mathbf{V_i^*}$ their corresponding standard deviation $\boldsymbol{S_i^*}$ and the mean values $\bar{\mathbf{v}}_\mathbf{i}$of row-centered log ratios $\mathbf{v_i}$as follows:

$$\mathbf{I_i} = \frac{\bar{\mathbf{v}}_\mathbf{i} - \mathbf{V_i^*}}{\mathbf{s_i}}; \qquad (5)$$

$$\mathbf{CND} - \boldsymbol{r}^\mathbf{2} = \sum_{\mathbf{i=1}}^{\mathbf{6}} \mathbf{I_i^2} \qquad (6)$$

These indices were then used for diagnosis. The indices were first ranked in increasing order, from the most limiting to the most abundant. Negative CND indices represent nutrient limitation and the most negative value indicates the most limiting nutrient among a set of nutrients. Positive CND indices are an indication of nutrient excess and the largest value indicates the nutrient present in greatest excess. When the CND-r^2 is close to zero, nutrient requirements are balanced and maximum plant growth is expected [19,20]. All calculations were performed using the Microsoft Excel 2013 software.

3. Results

3.1 Maize yield

Application of biochar increased maize yield by 55% above the control i.e. from 3.6 to 5.6 t $\mathrm{ha^{-1}}$ during the first production period and by 54 % above the control i.e. from 1.3 to 2 t $\mathrm{ha^{-1}}$ during the second production period (Tables 2 and 3). During the first production period, the maximum yield obtained was 8.33 t $\mathrm{ha^{-1}}$, with T4 (CCB and straw) and T2 (CCB) treatments. The minimum yield was 1.67 t $\mathrm{ha^{-1}}$ on control plots with T1 (fertilizer + straw). During the second production period, the highest recorded yield was 3.75 t $\mathrm{ha^{-1}}$ on plots receiving T4, while the minimum obtained was 0.42 t $\mathrm{ha^{-1}}$ on control plots with T1 (Table 2). Cate Nelson analysis (paragraph 3.2) also revealed that all high yields were recorded on biochar-amended FR (T4 and T2) during the first production period.

Table 2: Minimum, maximum, average and standard deviation of yield of maize yield during two production periods

Parameters	*Production period 1*					*Production period 2*				
Treatments	T1	T2	T3	T4	T5	T1	T2	T3	T4	T5
Yield (Maximum value in t $\mathrm{ha^{-1}}$)	5.00	8.33	8.00	8.33	7.00	2.50	3.67	2.58	3.75	3.42
Yield (Minimum value t $\mathrm{ha^{-1}}$)	1.67	4.17	2.50	3.33	3.33	0.42	0.75	0.58	0.42	1.08
Average yield (t $\mathrm{ha^{-1}}$)	3.61	6.11	5.22	5.83	5.08	1.33	2.14	1.76	1.77	2.38
Standard deviation (t $\mathrm{ha^{-1}}$)	1.11	1.46	1.77	1.75	1.41	0.80	1.19	0.78	1.28	0.78

T1= Fertilizer + straw; T2 = Fertilizer + CCB; T3 = Fertilizer + EB; T4 = Fertilizer + CCB + straw; T5 = Fertilizer + EB + straw; Fertilizer = N-P-K (20-10-10) at 200 kg $\mathrm{ha^{-1}}$ and urea (46-0-0) at 100 kg $\mathrm{ha^{-1}}$

3.2 Maize nutrition and compositional nutrient analysis

Following Cate Nelson analysis, during the first production period 87% of the population of maize was below the determined yield cut-off value of 6.77 t $\mathrm{ha^{-1}}$,the corresponding χ^2 value with 6 df was 2.52 compared to the calculated CND-r^2 value of 3.28. During the second production period, 93% of the maize population fell below the cut-offyield of 3.67 t $\mathrm{ha^{-1}}$with a corresponding χ^2 value with 6 df of 1.85 while the calculatedCND-r^2 value was 5.24. During the first production period, average total N concentration of high yielding plants was 2.43 % and that of low yielding plants 2.27%. For the second production period, both high and low yielding leaf N concentration was 2 %. Leaf phosphorus concentration range from 0.15-0.17% at tasselling (Table 4) during both production periods. The CND indices also indicated P deficiency in plants during the first production period, both in treated and control plots (Table 5). Data from [12] show that soil pH and organic carbon are the only measured soil parameters that were statistically different in response to the biochar treatment

Table3: Analysis of variance (ANOVA) of maize yield and leaf nutrient concentrations, as influenced by the production period, the treatment and soil management (degree of freedomand p-values)

Parameters	*DF*	*N*	*P*	*K*	*Ca*	*Mg*	*Yield*
Treatments versus control							
Production period (PP)	1	0.20	**0.10**	**<0.0001**	0.56	0.68	**<0.0001**
Treatment (T)	4	0.90	0.50	0.41	**0.01**	**0.01**	**0.01**
T * PP	4	1.00	1.00	0.47	0.50	0.84	**0.03**
Soil tillage mode (STM)	1	0.20	0.90	**0.10**	0.21	0.76	0.67
STM * PP	1	0.90	1.00	0.38	0.50	0.25	0.11
T * STM	4	0.80	0.60	0.55	0.62	0.42	**0.08**
In between treatments							
Biochar type (BT)	1	0.60	0.30	0.11	0.17	0.57	0.29
PP	1	0.30	**0.0003**	**<0.0001**	0.54	0.70	**<0.0001**
BT * PP	1	0.90	0.60	0.21	0.62	0.94	**0.05**
STM	1	0.30	0.70	0.13	0.28	0.86	0.65
BT * STM	1	0.30	0.40	0.12	0.81	0.26	0.91
STM * PP	1	1.00	0.40	**0.07**	0.72	0.20	**0.09**
Straw (S)	1	0.70	0.70	0.98	0.39	0.69	0.89
BT * S	1	0.40	**0.09**	**0.07**	0.18	0.85	0.40
S * PP	1	1.00	0.80	0.12	0.32	0.24	0.46
S * STM	1	0.40	0.40	**0.10**	0.24	0.49	0.17

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N.B: Figures in bold are values significant at 10 % confidence level

Table 4: Optimum leaf nutrient concentration for maize in New Zealand and USA (other studies), compared to high yielding plant leaf nutrient concentrations of the present study

Nutrient	*Unit*	*New Zealand Maize**	*United States Maize**	*Production period 1*		*Production period 2*	
				Treated plots	*Control plots*	*Treated plots*	*Control plots*
N	mg g^{-1}	2.25 - 3.30	2.76 - 3.50	2.43 ± 0.10	2.44 ± 0.09	2.15 ± 0.25	2.13 ± 0.44
P	mg g^{-1}	0.18 - 0.32	0.25 - 0.40	0.12 ± 0.02	0.12 ± 0.01	0.12 ± 0.02	0.12 ± 0.02
K	mg g^{-1}	1.70 - 3.00	1.70 - 2.50	1.40 ± 0.11	1.36 ± 0.00	1.59 ± 0.11	1.43 ± 0.01
Ca	mg g^{-1}	0.40 - 0.80	0.20 - 1.00	0.26 ± 0.01	0.16 ± 0.00	0.25 ± 0.00	0.15 ± 0.05
Mg	mg g^{-1}	0.13 - 0.30	0.20 - 0.50	0.28 ± 0.02	0.18 ± 0.01	0.25 ± 0.01	0.19 ± 0.01

***** Adapted from [23]

4. Discussion

4.1 Maize yield in response to biochar application

The obtained yield is in agreement with the range of 6-9 t ha^{-1} expected in the region with improved seeds. [24] reported increased maize yields of 2.2 t ha^{-1} over the control with biochar-amended ferralsol. [11,26]also reported increases in maize yield due to biochar amendment ranging from 20% to 140% above the control on a Colombian savannah oxisol. The positive effect of biochar on yield was more important during the first production period compared to the second (p=0.03), potentially because of better availability of nutrients with fertilizer additions. Biochar also positively interacted with FR, contributing to a better yield during the first production period (p=0.08); the CCB interaction with FR was found to be the most effective (p=0.05) (Table 3). These results demonstrate that biochar addition benefits plant growth and improves maize yield on oxisol soil, during two consecutive production periods (Table 3). More specifically, CCB (T2 and T4) appears to be the most appropriate biochar amendment when used on FR plots.

4.2 Nutrient concentration and Compositional nutrient diagnosis (CND) of maize leaves

The CND-r^2 distribution for maize in this experiment did not follow χ^2 distribution as previously assumed [4,21]. Similar results were obtained by [27]. During the first production period, average total N concentration of high and low yielding plants, fell between the accepted range of 2.25 % - 3.50 % [23], Table 4); this was also the case during the second production period. The above presumes that N absorption by plants was not a problem, since initially supplied N (mineral fertilizer) was sufficient to meet crop needs during this first production period (Table 1). But in the field, we observed that plants were less vigorous and yellowish during the second production period compared to the first. This is supported by CND indices (Table 5) which indicate leaf N deficiencies during the second production period. However, statistical analysis (Table 3) did not detect any difference in N concentration of maize leaf tissues irrespective of biochar treatment, biochar type, soil tillage mode or production period. Soil analysis also indicated no statistical difference in soil N concentration of treated and non-treated plots from the beginning throughout the two production periods [12]. This indicates no specific retention of the initially applied N due to biochar application or its immobilization due to the high soil carbon content. We thus argue for the contribution of other nutrients or parameters to explain the observed statistical difference in yield.

No difference in P leaf tissue concentration due to biochar addition or soil tillage mode was observed at 10% confidence level interval (Table 3). These are contrasting as initially supplied P (Table 1) was adequate to meet plant needs; its absorption and use by the plant might have been hindered. Duncan[28]argued that in acid soils (pH 4.5 to 6) soluble inorganic phosphorus is fixed by aluminium and iron resulting in substantial lock-up of P. Concentration of P in maize leaves significantly declined during the second production period, which may have contributed to the observed yield decrease. Leaf K concentration of maize significantly increased during the second production period compared to the first, independently of treatment ($p < 0.0001$), but remained below the acceptable range of 1,70 % to 3 % (Table 4). The CND indices also showed that K was deficient during the first production period in all plots, but only deficient in control plots during the second production period. As for P, initial K supply to soil was adequate (Table 1) and its deficiency could mainly be the result of poor absorption by plants. Beaton [29]reported that important reductions in yield levels can occur when K concentration is inadequate to fulfil crop requirements. This is referred to as “hidden hunger”; as such, K deficiency could have contributed to the high percentage of low yielding populations in both production periods, and more specifically to the lower yield observed in control plots during the second period. Also during this production period, leaf Mg and Ca concentration were significantly higher in maize leaf tissues of biochar treated plots compared to that of control plots (p= 0.01). Similar results were reported by Major [11]who noticed a significant higher Ca and Mg contents of maize flag leaves at tasselling in treated plots using wood biochar. This is a result of biochar application (Table 1) since they were the only supplementary source of Mg and Ca to soil. These elements were thus well absorbed by the plants. However, Mg was still highly deficient in treated plots, while Ca was deficient in all plots, with deficiencies being more pronounced in control plots (Table 5).

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Table 5: CND indices values of treated and control plot for each production period

Production period 1				*Production period 2*			
Treated Plots		*Control plots*		*Treated Plots*		*Control plots*	
Indices	*Values*	*Indices*	*Values*	*Indices*	*Values*	*Indices*	*Values*
IP	-1.10	*IK*	-0.89	*IMg*	-1.29	*IK*	-0.75
IK	-0.43	*IR5*	-0.46	*Ica*	-0.19	*IN*	-0.51
IR5	-0.20	*IP*	-0.25	*IN*	-0.07	*IR5*	-0.45
Ica	0.12	*IMg*	-0.01	IK	0.15	*Ica*	-0.32
IMg	0.85	Ica	0.13	IR5	0.28	IMg	0.00
IN	0.90	IN	1.87	IP	0.66	IP	0.88
CND-r2	*6.45*		*4.04*		*4.66*		*5.53*

N.B. Deficient nutrients are in bold-italic; relatively to “0”, lowest values indicate most deficient nutrients and higher values indicate nutrients in excess.

Soil pH and organic carbon are the only measured soil parameters that responded positively to biochar treatment. It is thus likely that these were the main soil parameters responsible for improvement in yield observed in biochar-treated plots, through increased availability of soil nutrients. [30] argued that availability of nutrients for plant uptake is directly related to soil pH; soil with acidic pH (3-5.5) has generally higher concentrations of heavy metals, Al and Fe toxicities and lower CEC. During the first production period, P and K were deficient in both treated and control plots but Mg was only deficient in control plots. During the second production period Ca and N were deficient in both treated and control plots while Mg was deficient only in treated plots and K deficient only in control plots. Therefore, Mg could have been the main critical nutrient that contributed to the yield increase observed between control and treated plots during the first production period. A K deficiency could have contributed to the lowest yield in control plots during the second production period.

5. Conclusion

This study in an operational field trial demonstrated that a single biochar application at a rate of 15 t ha^{-1}, to a nutrient-poor, acidic tropical soil (oxisol), improved crop yields during two cropping seasons by 54 % above the control treatment. This indicates that biochar could be a valuable asset for the management of agro-ecosystems in humid tropical regions, where subsistence agriculture is practiced frequently on highly-weathered oxisols. Mechanisms by which biochar interacts with the oxisol may include improved pH and organic carbon, thus better availability of P and other cations such as Mg and K in the rooting zone. The CCB char in particular positively interacted with the furrow and ridges tillage mode after application in the first production period, contributing to a better yield compared to EB char, however, this effect was limited in time (not observed during the second period). Maize plants were globally nutritionally unbalanced in both treated and untreated plots; P, Mg and K were identified as the most limiting nutrients. This suggests a need for further studies aiming to improve current maize fertilization practices on oxisols. Also, a longer term study is needed to determine when the positive yield effects of biochar application decline, in order to program further amendments.

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