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EFFECTIVENESS OF RICE-HUSK BIOCHAR IN SUSTAINABLE ARABICA COFFEE PRODUCTION IN SOUTH EASTERN UGANDA

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ABSTRACT

The study aimed at determining the effectiveness of rice-husk biochar in improving the growth and yield of Arabica coffee in southeastern Uganda. Two experiments were run from January 2023 to July 2024, on mature coffee and on coffee seedlings. The mature coffee experiment involved applying plain and fortified biochar on coffee at 0, 300, 600, 1200 and 2400 g/tree in Bulambuli and Kween Districts. The coffee seedlings trials involved applying plain and fortified biochar to polypots at varying biochar-to-soil ratios (0, 25, 50, 75, and 100%) before placing the coffee seedlings. The seedlings were watered daily, after two days and after three days. Results from the mature coffee showed that soil organic matter and nitrogen increased with application of biochar, especially the fortified. However, below biochar application rate of 2400g/tree, P and K availability reduced with increase in fortified biochar, but increased with increase in plain biochar. Fortified biochar supported more vegetative growth than plain biochar at 1200–2400 g/tree, though yield differences between the two were not significant. However, incremental returns on investment were higher for plain than fortified biochar. Watering the seedlings at two-day interval promoted better root and leaf development than daily watering.

Keywords: Arabica coffee, biochar, fortified biochar, coffee yield, soil amendment

1.0 INTRODUCTION

Coffee is a key pillar of Uganda's economy, contributing to foreign exchange earnings, employment, and a key commodity in the country's value addition and agro-industrialization agenda as stipulated in Uganda's Vision 2040. The crop is grown by more than 1.7 million households, majority of whom (> 80%) are smallholder farmers (1). However, it directly employs over 5 million people along the coffee value chain. Uganda produces both Arabica and Robusta coffee. Arabica coffee is majorly grown in the highland agro-ecologies, on approximately 90,000 hectares of land, whereas Robusta thrives in the lowland areas on approximately 500,000 ha of land (2). Nonetheless, a significant decline in coffee exports has been reported of recent, specifically by 33.03% for Robusta and 9.45% for Arabica (3). The decline has been attributed majorly to harvest and logistical challenges. However, inadequate access to both organic and inorganic fertilizers has equally been identified as a challenge for Ugandan farmers, potentially impacting soil fertility and coffee yields. Biochar is a solid material obtained from the thermo-chemical conversion of biomass in an oxygen-limited environment. Biochar can be used directly as a product or as an ingredient within a blended product, to improve soil properties and/or resource use efficiency, to remediate and/or protect against environmental pollution, and as an avenue for GHG mitigation (4). Some coffee producing regions use few to no chemical fertilizers for crop growth or pesticides but could take advantage of biochar to increase crop yield and soil health and reduce GHG emissions. Biochar helps in buffering soil pH, improving soil structure, water retention, increasing nutrient uptake and encouraging microbial activities, enables coffee plants to sequestrate more carbon into the soil hence improving overall soil health. However, biochar efficiency is not well established in Uganda, especially for coffee.

Biochar can be made from many plant residues, including those of rice. However, for long, majority of farmers either burn rice-husks and straws or leave them to decompose in flooded rice paddies. These practices contribute to the release of harmful gases into the atmosphere such as Methane (CH_4), carbon dioxide and nitrous oxide, thus leading to environmental pollution. In fact, just in the agricultural sector alone, rice production is known to contribute about 10% of total greenhouse gas (GHG) emissions world-wide. Therefore, rice-based biochar was given priority in this study because promoting its production and use is a key contribution to carbon sequestration, reduced GHG emissions, thereby collectively contributing to a lower carbon footprint, a sustainable rice production, and to the global 'waste to resource' agenda (5). Preliminary evaluation of rice-based biochar on growth and yield of rice, tomatoes, vegetables, among other crops, revealed benefits ranging from reducing cost of production, increasing farm productivity, improving quality of farm produce, improving nutrition, reduced exposure to hazardous chemicals and environmental conservation (6). Unfortunately, similar studies have never been conducted on coffee. Precisely, this study was designed to help provide scientific evidence on efficacy of biochar utilization in sustainable Arabica coffee production in Uganda in the face of very expensive and environmentally unfriendly inorganic fertilizers. Many companies in Uganda are currently registered and certified by Ministry of Agriculture Animal Industry and Fisheries (MAAIF) to produce biochar from locally available crop residues. However, no data exists as supporting evidence for the effectiveness of biochar in improving soil health, growth and yield of Arabica coffee. Therefore, the major objective of this study was to determine the effects of rice-husk biochar usage in sustainable Arabica coffee production in south eastern Uganda. The specific objectives were to, (i) determine suitable biochar application rates in existing coffee plantations, and (ii) assess the effect of rice-husk biochar on growth of coffee nursery seedlings, water use efficiency and survival.

2.0 MATERIALS AND METHODS

Study sites

To assess how effective biochar is in sustaining coffee production, two studies were conducted on the Mt. Elgon slopes of south eastern Uganda, specifically in the districts of Kween and Bulambuli. Kween is situated at approximately 1°23'14"N latitude and 34°34'24"E longitude, with an elevation of 2,391 m asl. On the other hand, the Bulambuli site was established at Buginyanya Zonal Agricultural Research and Development Institute (BugiZARDI), Masira Sub-county in south Eastern Uganda. The institute is situated at an elevation of 1,900 m asl and lies at latitude 1.25°N and longitude 34.38°E.

Experimental designs

The two studies conducted were: (i) biochar utilization on mature coffee, and ii) biochar utilization in a controlled coffee seedlings nursery. Both studies aimed to evaluate the agronomic response of coffee to various rates and types of biochar, focusing on improving application and enhancing plant health, growth, and survival. We used rice-husk biochar that was either plain or enriched with nutrients (fortified) before application. Other details concerning the methodology of each of the two studies, is explained below.

a) The mature coffee experiment

The mature coffee study was conducted in two coffee-growing districts within the Mt. Elgon highland region of Uganda, namely Kween and Bulambuli. Mature Arabica coffee fields (8 – 10 years old), planted at recommended spacing of 2.4 x 2.4 m were identified and the treatments laid out in a RCBD but in a split-plot arrangement, with two replications per site. The main plot factor was the type of biochar, which included plain biochar and fortified biochar. The subplot factor involved five application rates of the biochar: 0 g/tree (control), 300 g/tree, 600 g/tree, 1200 g/tree and 2400 g/tree, each applied on four plants. Both plain biochar and fortified biochar were applied in two split doses to ensure proper incorporation and reduce losses due to leaching. Biochar was applied around the base of established mature Arabica coffee trees. Both the plain and fortified biochar was obtained from Bongomin Group Ltd who make it from rice-husks (as the major organic material) following the method described by Lehmann and Joseph (7). Data were collected during crop growth on stem girth, plant height, number of primary branches, pests and disease symptoms at an interval of six months beginning from July 2023 until July 2024. Similarly, fruit yield parameters like cherry weight were collected in three phases but at short intervals of two weeks during the harvesting season. Soil samples were collected before and after treatment application to track changes in soil chemical properties. The sampling method and preparation of samples followed procedures outlined by Okalebo et al. (8) before delivery to the plant analytical laboratory at the College of Agricultural and Environmental Sciences (CAES), Makerere University Kampala Uganda for analysis. The key properties analysed included pH, organic matter (O.M), nitrogen (N), phosphorus (P), potassium (K), and soil texture.

b) The coffee nursery experiment

The coffee nursery experiment was established in Kibanda Subcounty, Bulambuli District in south eastern Uganda. The nursery beds were organised in a Randomized Complete Block Design (RCBD), but in a factorial arrangement. Thus, the main factor was the biochar type, either fortified or plain. The subplot factor consisted of four biochar-to-soil ratios by volume: 100% biochar (1:0), 75% biochar (3:1), 50% biochar (1:1), and 0% biochar (0:1, control). The Arabica coffee seedlings were raised in the biochar-soil mixtures properly placed in poly pots under a shade net. The soil used in the poly pots was forest topsoil that was sourced from a nearby undisturbed area with the aim of maintaining uniform fertility across treatments. The biochar used was obtained from Bongomin Group Ltd as described under the mature coffee section. All seedlings received uniform amounts of water that was applied manually using watering cans. Frequency of watering/irrigation was closely monitored and recorded in order to determine its effect on the vigour of coffee seedling placed in a biochar-soil mixture. Data were collected on seedling height, number of leaves, pest and disease incidence, and soil moisture content at three months intervals from 3 months after planting (3 MAP) up to 9 MAP. We also monitored seedling survival rate over a defined period and recorded visual vigour scores.

Statistical analysis

All quantitative data from the mature coffee field and nursery experiments were analysed using Analysis of Variance (ANOVA) in Genstat statistical software. Testing was conducted to ascertain the significance of main and interaction effects between biochar type and application rate at a 5% probability level. Post-hoc comparisons were conducted using Fischer's Least Significant Difference (LSD) test, where significant differences appeared ($P \leq 0.05$). Net profits following the use of the two types of biochars on coffee were calculated as Total Revenue – Biochar costs. Incremental Returns on investment (ROI) were calculated as (Additional net profits/Additional cost of biochar) x 100 (9).

3.0 RESULTS

3.1 Effectiveness of biochar in improving soil healthy of mature coffee fields

The soil nutrient analysis results showed that soil organic matter (o.m) gradually increased with application of biochar to mature coffee in the field (Fig. 1a.).

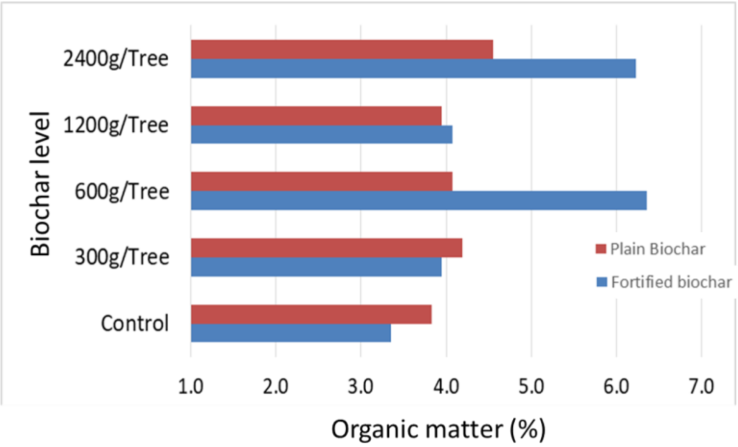

Figure 1a: Effect of biochar application on soil organic matter in mature coffee fields

Fortified biochar, when applied at 600g/tree and 2400g/tree, resulted in the highest level of soil organic matter of 6.4% and 6.2%, respectively. This was above the control of 3.4%, making an incremental addition of 3.0% o.m in the soil. Fortified biochar is enhanced with essential nutrients and these could have favoured activity of microbes in decomposition of organic matter back into the soil, hence the observed increase in o.m where high levels of fortified biochar were applied. Results further showed that application of biochar (especially the fortified biochar) increased availability of nitrogen in the soil, though not significantly across treatments (Fig. 1b), with 0.19% in the control to 0.3% in trees that received 2400g/tree. Thus, an increase of 0.11% of available nitrogen in the soil was realized. The availability of P in mature coffee fields was highly influenced by the type of biochar applied. Increase in available P was at its maximum when 300g/tree of fortified biochar was applied to the mature coffee (Fig. 1c).

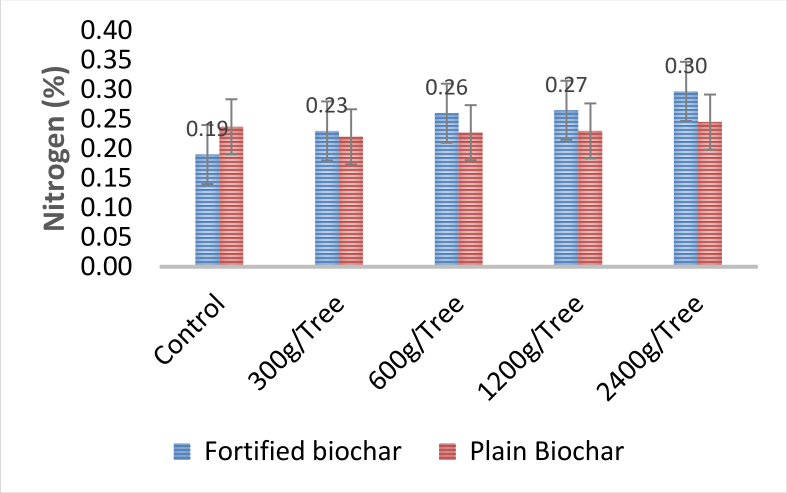

Figure 1b: Effect of rice-husk biochar application on availability of nitrogen in mature coffee fields

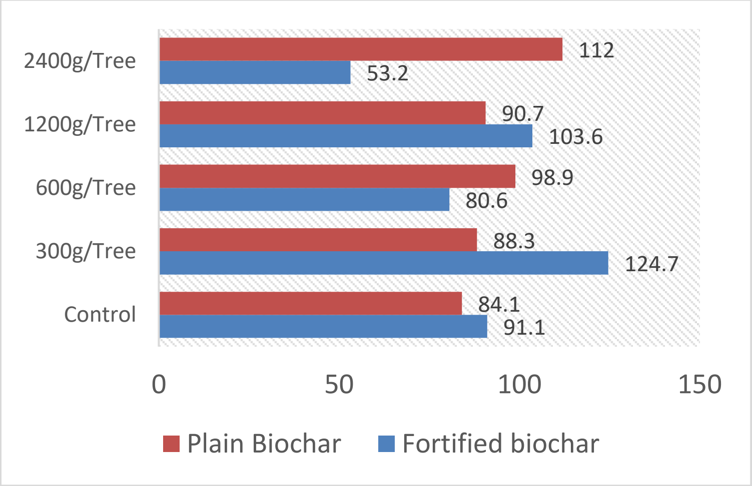

Figure 1c: Effect biochar application on availability of phosphorus in mature coffee fields

The 300g/tree application contributed to 33.6 mg/kg of available P in the soil in comparison to the control. However, available P gradually declined to a minimum when there was 2400g/kg of fortified biochar applied, implying that higher levels of fortified biochar reduced P availability in the mature coffee fields. However, the trend was different with the application of plain biochar, where available P increased gradually with increase in the rate of plain biochar. Thus, at 300g/tree, plain biochar contributed 4.2 mg/kg of P compared to a contribution of 27.9 mg/kg at 2400g/kg. Similar to P, K availability reduced with increase in the levels of fortified biochar except at 2400g/tree, and the reverse was true for plain biochar (Fig. 1d).

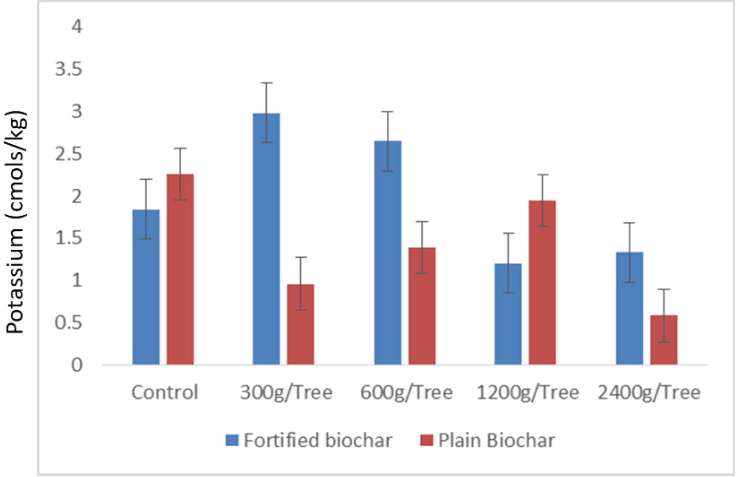

Figure 1d: Effect of biochar application on soil available potassium in mature coffee fields

3.2 Contribution of biochar in rehabilitating mature coffee plantations

The Analysis of variance (ANOVA) showed biochar types having significant effects ($P < 0.05$) on leaf length, plant girth, leaf area, number of primaries with secondary and number of internodes (Table 1).

Table 1: Analysis of variance mean squares for selected growth and yield parameters of mature coffee plantations

Source of variation	d.f.	Leaf length (cm)	Canopy Diameter	Stem girth	Leaf area	No of primaries with secondary	No of internodes	Total wt of fresh cherries (g) (x1000)	Total fresh wt of cherries/tree (g)
Location	1	53.8***	22884***	155.9*	2178***	223**		1.72E+07	1.07E+06
Treatments	4	1.82*	555	45.5	49.8	57.9	53.4	1.11E+09***	6.94E+06***
Biochar type	1	5.27**	207	165.7*	190*	173*	290*	7.64E+06	4.77E+05
Location x Treat	4	1.57*	386	31.3	53.2	16.0		8.69E+05	5.43E+04
Location x Biochar type	1	0.09	1350*	6.7	0.2	83.0		1.08E+06	6.79E+04
Treat x Biochar type	4	1.07	964*	7.6	75.1	24.0	67.3	1.10E+07	6.92E+05
Location x Treat x Bio	4	0.32	1132*	23.9	15.0	52.9		1.07E+07	6.69E+05
Residual	28	0.54	342	23.0	33.2	28.7	65.5	1.37E+7	8.56E+05

Treatment, also abbreviated as Treat refers to the biochar application rates: 0 (Control), 300g/tree, 600g/tree, 1200g/tree and 2400g/tree. Biochar type, also abbreviated as Bio. *, **, and *** represent significance at $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$.

On the other hand, treatments had significant effects ($P < 0.05$) on leaf length and all the yield parameters of total weight of fresh cherries, total weight of dry cherries, weight of fresh cherries per tree, weight of dry cherries per tree. Location x Biochar interaction significantly affected canopy diameter and the bearing nodes. Biochar x treatment interaction only had a significant effect on canopy diameter. Whereas the highest leaf length was achieved at biochar application rate of 600g/tree, the highest weight of cherries (both fresh and dry) was achieved at the highest biochar application rates of 1200g/tree and 2400g/tree, and these were significantly higher than the control (Table 2).

Compared to plain biochar, fortified biochar had significantly higher effects ($P < 0.05$) on leaf length, leaf area, plant girth and number of primaries with secondary (Table 3). However, whereas the yield parameters were practically higher under fortified biochar, statistically, there was no significant difference with the plain biochar. For example, there was an observed difference of 196 g of total fresh weight cherries (locally called *kiboko*) per tree under fortified biochar compared to plain biochar which in monetary terms gives an advantage of only Uganda Shillings One thousand three hundred seventy-two (UGX 1372), which is about US $ 0.4.

Table 2: Effect of biochar application rates on performance of mature coffee on Arabica coffee in eastern Uganda

Application rate	Leaf length (cm)	Total fresh cherries wt (g)	Total dry cherries wt (g)	Total fresh cherries wt/tree (g)	Total dry cherries wt/tree (g)
0 g/tree (Control)	12.7	871	513	217.8	128
300 g/tree	12.3	2299	1434	574.8	358
600 g/tree	13.4	2273	1221	568.3	305
1200 g/tree	12.4	5350	2807	1337.5	702
2400 g/tree	12.6	9189	4306	2297.3	1076
LSD (P = 0.05)	0.67	3391.2	1812.7	847.81	453.2

Table 3: Effect of biochar type on performance of mature coffee on Arabica coffee in eastern Uganda

Biochar type	Leaf length (cm)	Plant Girth (cm)	Leaf area (cm^2)	No of primaries with secondary	No. of internodes	Total fresh cherries wt (g)	Total dry cherries wt (g)	Total fresh cherries wt/tree (g)	Total dry cherries wt/tree (g)
Fortified	13.0	40.4	50.7	18.0	47.3	4388	2234	1097	558
Plain	12.3	36.8	46.8	14.3	42.5	3605	1879	901	470
LSD (P = 0.05)	0.43	2.78	3.34	3.10	4.81	2145	1146	536	287

The net profit where either plain or fortified biochar was applied was three times higher compared to the control with no any form of biochar applied (Table 4). Incremental returns on investment (ROI) were highest for Plain Biochar (35,621 %) compared to fortified biochar (17,772%), corresponding to net returns of UGX 8,548,952 and UGX 8,530,744 per hectare, respectively. Thus, holding all other production factors constant, the additional net benefit attributable to plain biochar was 356.2 times its acquisition cost. This is much higher compared to only 177.7 times for fortified biochar.

Table 4: Net returns to investment in biochar on mature coffee

Indicator	Total revenue (UGX/ha)	Biochar cost (UGX/ha)	Net profit (UGX/ha)	*ROI (%)
Fortified Biochar	13,330,744	4,800,000	8,530,744	17,772
Plain Biochar	10,948,952	2,400,000	8,548,952	35,621
Control	2,649,136	-	2,649,136	N/A

Note: 1 US Dollar is approximately UGX 3500. *Incremental Returns on investment for only the biochar expressed as a percentage.

3.3 Effect of biochar application on growth and yield of coffee seedlings in the nursery

Analysis of variance showed that, the period from planting, hereafter referred to as months after planting (MAP), had a significant effect on plant height and the number of leaves of the coffee seedlings in the nursery, but not on the root length and the root biomass. The biochar type (plain biochar verses fortified biochar) and watering regime, significantly affected only the number of leaves, but not the plant height, the root length and the root biomass. The treatments, also referred to as the biochar to soil ratio volumes, significantly affected the number of root primaries but none of the other variables in the study. Likewise, MAP x Biochar type and MAP x Watering regime had significant influence on only the number of leaves, whereas Treatment x Watering regime significantly influenced the number of root primaries. No any other two-way significant interaction effects were observed in the study. Fortified biochar application resulted in a consistent improvement in early plant growth compared to plain biochar (Fig. 2a). Thus, plants treated with fortified biochar attained greater height (9.5 cm vs. 9 cm), produced more leaves (5.9 vs. 5.5), and developed a higher number of root primaries (23 vs. 22) compared to plants treated with plain biochar. These differences, though statistically trivial, suggest that fortified biochar enhances both above-ground and below-ground early growth parameters of young coffee seedlings, due to the inherent nutrient enrichment.

The biochar-to-soil ratio volumes had significant effects on dry weight of roots and the number of root primaries (Fig. 2b), but not plant height, number of leaves, root biomass and root length. Largely, better growth parameters were observed with less biochar to soil ratio than with more biochar to soil ratio. For example, number of leaves, dry weight of roots, root biomass and number of root primaries were all at their highest when the growth medium was 25% biochar, and at their lowest when the growth medium was 100% biochar. Specifically, dry weight of roots was 12.2 g at 25% biochar compared to only 5.9 g at 100% biochar. Similarly, number of root primaries was highest (25.5) at 25% biochar compared to only 20.4 root primaries at 100% biochar and 19.3 root primaries at 50% biochar.

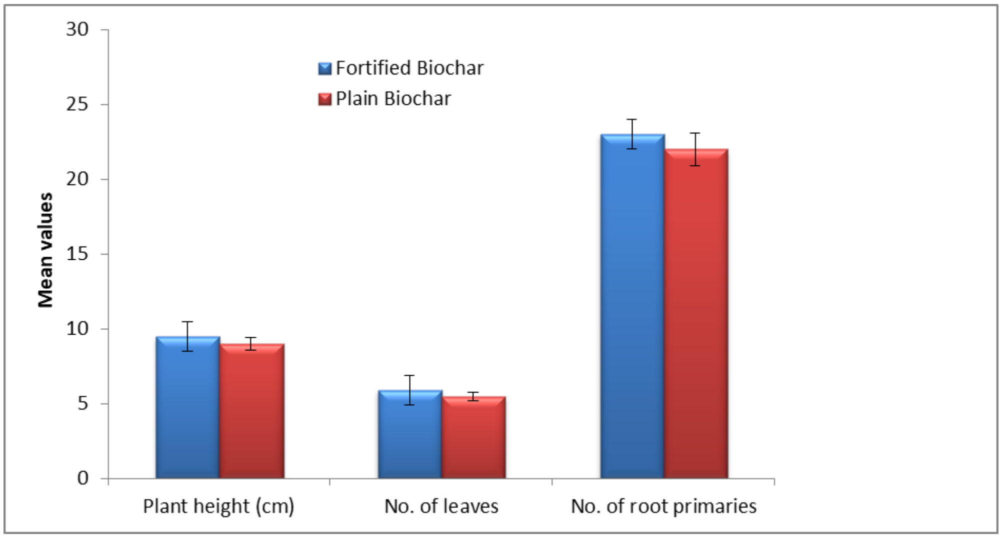

Figure 2a: Effect of biochar types on growth of the Arabica coffee seedlings in nursery

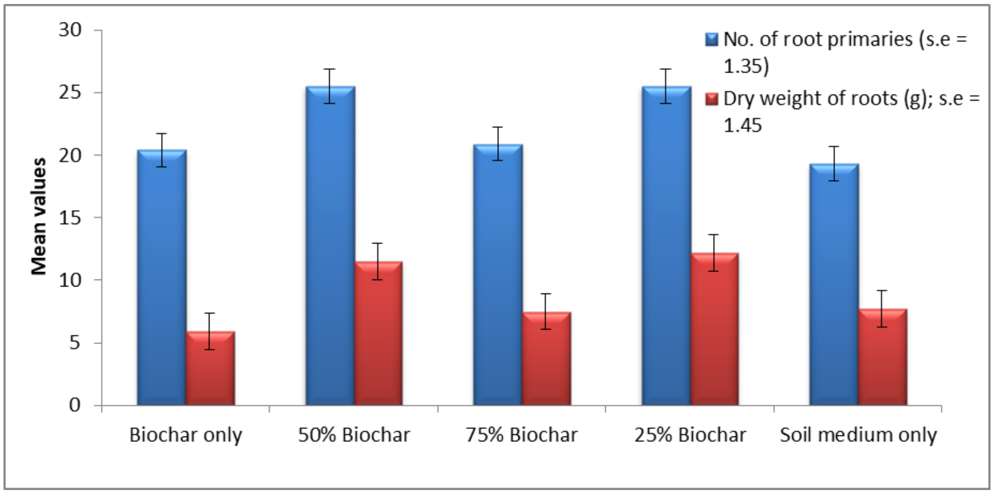

Figure 2b: Effect of four biochar-to-soil ratios on number of root primaries of Arabica coffee seedlings at three months after planting

Watering morning and evening on a daily significantly ($P < 0.05$) increased the dry weight of roots, but not the number of root primaries of the coffee seedlings (Table 5). The numbers of leaves were lowest where watering was conducted after three days, but highest where watering was after two days. Interestingly, even the number of root primaries was highest (24.2 root primaries) at two days watering interval, followed by three days (23.3 root primaries) and lowest at daily watering (19.5 root primaries). Plant height of the seedlings increased with time, but more exponentially with the application of biochar.

Table 5: Effect of watering frequency on growth and survival of the coffee seedlings

WATERING_REGIME	Plant height (cm)	No. of leaves	Dry wt of roots (g)	Root biomass (g)	Root length (cm)	No. of root primaries
Morn-Eve After Three Days	9.0	5.5	7.9	14.3	13.6	23.3
Morn-Eve After Two Days	9.3	6.0	7.4	13.0	13.6	24.2
Morn-Eve Daily	9.5	5.7	11.5	18.6	11.9	19.5
LSD (P= 0.05)	0.75	0.4	4.4	6.4	2.7	4.1

However, a more significant increase was realised from 6 and from 9 MAP (Fig. 3a). Fortified biochar resulted in a significantly higher increase in plant height than plain biochar, but only at the early stages (3 MAP) of plant growth. At 9 MAP, under fortified biochar and plain biochar, plant heights were not significantly different. The numbers of leaves were also observed to increase with time with application of biochar, but with a more significant increase from 6 and 9 MAP (Fig. 3b).

At 3 and 6 MAP, fortified biochar had significantly more number of leaves than plain biochar. At 9 MAP, plain biochar enhanced leaf numbers more than the fortified biochar. The two scenarios suggest that fortified biochar is a good start-up soil nutrient additive compared to plain biochar. Indeed, fortified biochar is rich in mineral fertilisers which is not true with plain biochar. Both fortified and plain biochar performed well in improving plant height and number of leaves at 9 MAP simply because, by the 9th month, the fortified biochar has lost the fortification (mineral fertilisers) and has remained plain like the plain biochar.

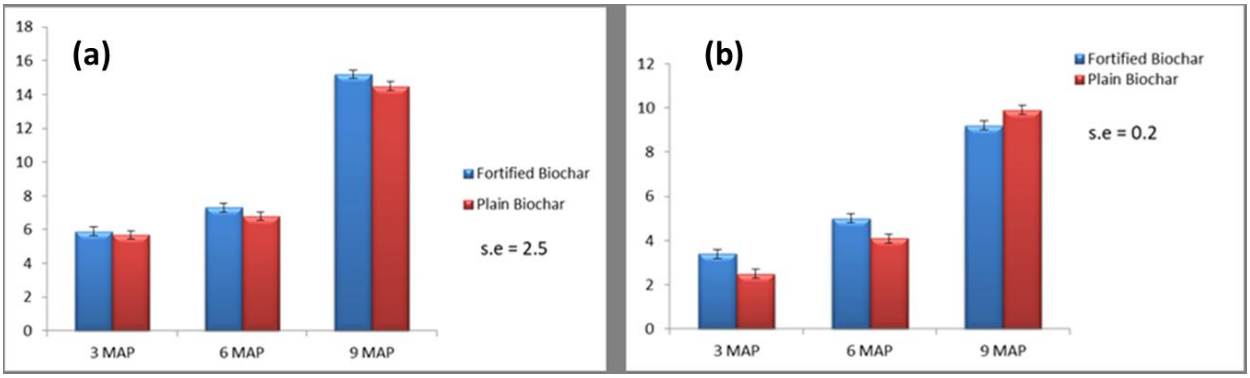

Figure 3: Effect of biochar on (a) plant height and (b) number of leaves of the coffee seedlings at 3, 6 and 9 months after planting (MAP)

4.0 DISCUSSION

The study revealed that increase in organic matter (o.m) to the soil as a result of addition of plain biochar was 0.72%. Similarly, Oladele et al. (10) observed a steady rise in microbial activity following the application of rice-husks biochar in the soil. This additional input to the soil is a key factor in sustainable crop production. The increase in available N following addition of the rice-husks biochar in the soil was reported by Linam et al. (11). The decline of P to very low levels at 2400g/tree (maximum rate) of biochar, implies that fortified biochar reduced P availability in the mature coffee fields. It is probable that the fortified biochar fixed or absorbed the P amidst the increased activity of microbial organisms. It is also possible that P transformation took place, thus making it unavailable at higher levels of fortified biochar. Consequently, available P increased gradually as the rate of plain biochar increased. Similarly, Bu et al. (12) reported increase in available P and greater activities of microbes when plain rice-husks biochar were used.

According to Lehmann & Joseph (7), when biochar is fortified with P and K, it begins operating as a slow-release, nutrient-retentive carrier, thus ensuring enhanced nutrient use efficiency that is much better than where plain biochar or inorganic fertilisers have been applied. Also worth noting is the fact that the fortification process makes the P and K ions to be adsorbed onto the biochar surfaces thereby reducing their immediate solubility and susceptibility to leaching after soil application. Furthermore, through electrostatic adsorption process, the high surface area, porosity, and cation exchange capacity (CEC) of biochar plays a strong role in enhancing the retention of K^+, thereby limiting potassium losses in highly weathered soils. In acidic soils, biochar can reduce P fixation by Fe and Al oxides by increasing soil pH and the number of alternative sorption sites, thereby maintaining P in more plant-available forms (13). Additionally, biochar surfaces enhance the development of organo-mineral complexes that can only allow gradual release of nutrients into the soil solution. In terms of the microbial community, fortified biochar creates a favourable environment for phosphate-solubilising and K-mobilising microorganisms, thus enhancing nutrient recycling and continued availability. Overall, the superior performance of fortified biochar compared to plain biochar as observed in this study supports the need for supplementing biochar with nutrients and/or microbial amendments in order to realize significant agronomic effects (6). The variation in response to biochar across sites is an indication that properties such as soil texture, organic matter content and the local climate affect biochar performance. Previous studies similarly reported that biochar does not behave uniformly across agro-ecological zones (14). Therefore, biochar application protocols that are site-specific for a perennial crop like coffee, where long-term stability of soil health is required, are necessary.

Although crop benefit of the fortified biochar was evident for vegetative traits, the lack of a significant increase in the yield components indicates a complex association of early vegetative vigour and final reproductive output. Nevertheless, any yield increase is worth the effort provided it increases the farmer's net income. Therefore, we can confidently recommend an application rate of 2400g of biochar per tree for maximum coffee yields, but applied in splits. This translates into 4 t ha^{-1} of biochar for a coffee field spaced at 2.4 x 2.4 m. The recommendation of 4 t ha^{-1} is however much lower than 7.5 t ha^{-1} and 27.6 t ha^{-1} as recommended for tomatoes and maize respectively by Kisekka et al. (15) and Wacal et al. (16), but using biochar from maize stovers. It is also much lower than a moderate application rate of 10 tons ha^{-1} recommended for paddy rice, using biochar from rice-husks. Therefore, when enhanced and applied correctly, rice-husk biochar can become a fundamental ingredient in mature coffee sustainable production systems due to its potential in recycling wastes, improving soil fertility, and in sequestering carbon (7). However, these findings support the need for a more comprehensive approach to biochar evaluation not only based on yield but also based on profitability and resilience.

The amazingly higher ROI observed for plain biochar (35621%) and fortified biochar (17772%) is a reflection of the differences in incremental cost relative to marginal benefits, rather than whole-enterprise profitability, simply because all the other production factors were held constant. Similarly, CIMMYT (17) reported very high percentage returns in a partial budget analysis and attributed it to the low additional cost of an input relative to the yield or revenue gains generated. Plain biochar's higher ROI suggests that, under the conditions of this study, its cost-effectiveness per unit of benefit exceeded that of fortified biochar. Despite the fact that fortified biochar had generated considerable profits, its higher acquisition cost curtailed the relative percentage gain. Similar studies emphasize that incremental ROI is appropriate for comparing technologies where only one factor varies, but it needs to be interpreted based on absolute net benefits to avoid overestimation of economic attractiveness (18).

In the coffee seedling nurseries, the ratio of soil to biochar was a key factor to efficient growth media. The 3:1 soil-biochar proportion presented the best effects in terms of dry root weight and the amount of root primaries. This is supported by earlier studies by Lehmann and Joseph (7), but also closer to recommendations by Bongomin group Ltd of one part topsoil to one part well-decomposed farm yard manure to one part biochar, and Safi Organics of two parts soil to one part biochar (19). Unfortunately, plain biochar was associated with slower growth, most probably due to its low nutrient content and high pH, which possibly limited nutrient availability. Regarding watering regimes, applying water daily improved the dry root weight, but watering once every after two days increased both the amount of root primaries and the number of leaves. It therefore implies that moderate water stress promoted root branching and increased nutrients foraging efficiency as earlier reported by Koevoets et al. (20). The improved root development, in particular, may contribute to better nutrient and water uptake efficiency during subsequent growth stages (6). In contrast, daily watering could restrict oxygen provision to the roots, thus discouraging root tip differentiation. Further research revealed that effects of biochar application on coffee seedling growth become more evident over time. For example, plant height and leaf number increased markedly between 6 and 9 months after planting. Notably, fortified biochar performed significantly better than plain biochar during the early stages of growth (3 MAP), a finding consistent with studies demonstrating the synergistic effects of combining biochar with nutrient amendments (21). However, by 9 MAP, the response to fortified and plain biochar by the coffee plants was almost in equal measure, suggesting that the initial nutrient boost from fortification is most beneficial during early seedling development.

5.0 CONCLUSION AND RECOMMENDATIONS

The study revealed that o.m and nitrogen gradually increased with application of biochar, especially the fortified type, to mature coffee fields. Whereas o.m increase reached its peak at 1200g/tree, N increase kept increasing up to 2400g/tree. On the contrary, P and K availability reduced with increase in the levels of fortified biochar except at 2400g/tree, and the reverse was true for plain biochar. These findings are much aligned to the growing body of evidence that biochar is most effective as a soil amendment when: used in combination with soil (rather than as a stand-alone substrate), fortified with essential nutrients, and applied under optimized irrigation/watering regimes. Improvement in nutrient uptake and yield from crop fields incorporated with biochar has frequently been attributed to increased soil pH, electrical conductivity (EC), organic carbon (OC), available N, P and K (22). Based on this study, the recommendation is to apply 2400 g (the equivalent of 4 t ha^{-1}) of biochar in two splits per tree to help rejuvenate mature coffee plantations. Also, the fortified type is more reliable for vegetative improvement of mature coffee plantations, though it had lower incremental returns on investment compared to the plain biochar. For Arabica coffee nursery seedlings production, it is best to use a 3:1 soil-to-biochar ratio (25% biochar). Lastly, growth and seedling development in the nursery is more pronounced when watering is conducted only once (both morning and evening) every after two days. In conclusion, rice-husk biochar is a promising component for sustainable coffee farming practices but may require performing more multiple season field trials to fully understand the sustained impacts of rice-husk biochar on soil health, microbial activity and coffee yield.

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