

Integrating compost and biochar as climate-smart soil amendments to enhance cocoa yield, profitability, and sustainability in Ghana

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Abstract

Declining soil fertility constrains cocoa productivity across Ghana's cocoa landscapes, while smallholder adoption of organic amendments remains limited. We evaluated combined applications of mineral fertilizer, compost and biochar under no-shade and medium-shade systems for cocoa productivity, soil fertility and profitability over two growing seasons (2022/2023–2023/2024) in moist and dry semi-deciduous zones of Ghana. A split-plot design comprised shade system as the main plot and five soil amendments as subplots: no amendment (T1), mineral fertilizer (T2), mineral fertilizer + biochar (T3), half-rate mineral fertilizer + compost without rock phosphate (T4), and half-rate mineral fertilizer + compost with rock phosphate (T5), replicated three times. Shade did not significantly affect pod load or bean yield, whereas all amended treatments significantly outyielded the control. By the second season, bean yield increased by 74–93% and 75–89% relative to the control in the moist and dry zones, respectively, with T5 consistently producing the highest yield. Amendments improved soil pH, organic carbon, total N, available P, cation exchange capacity and microbial biomass carbon, with the largest gains under T4 and T5. Stepwise regression identified nutrient use efficiency, nutrient release rate, cation exchange capacity, microbial biomass carbon, soil nitrogen, organic matter, and available phosphorus as key yield drivers, explaining 91% of yield variation, with soil nitrogen as the strongest predictor. Net income increased by up to 78% under T5 compared with 53% under T2. These findings suggest that partial substitution of mineral fertilizer with on-farm compost offers Ghanaian cocoa farmers a cost-effective, soil-fertility-building pathway to higher yields and profitability.

1 Introduction

Soil fertility decline is one of the major constraints affecting cocoa yield and sustainability in Ghana's cocoa landscapes (Kenfack Essougong et al. 2020; Akrofi-Atitianti et al. 2018; Baah et al. 2011). The primary cause of this decline is continuous cultivation without sufficient replenishment of soil nutrients, which over time results in nutrient depletion and reduced soil productivity (Doe et al. 2022; Gockowski and Sonwa 2011; Appiah et al. 1997). Conventional soil management techniques, such as the application of mineral fertilizers, have been used to address these problems, but the high cost of mineral fertilizers, coupled with their limited availability and accessibility to smallholder farmers, has hindered their widespread and sustained use (Nunoo 2014; Chianu et al. 2012). In this context, combining mineral fertilizer with organic nutrient sources such as compost and biochar represents a promising approach to improving cocoa yield and return on investment in Ghana's cocoa landscapes. Compost is a rich source of organic matter and essential nutrients produced through the decomposition of organic materials, while biochar is a stable form of carbon produced through the pyrolysis of biomass (Hassan et al. 2023; Khan et al. 2022). Incorporating compost and biochar into cocoa farming systems not only supplies essential nutrients but also enhances soil organic matter content, water retention and microbial activity, thereby promoting soil health and fertility (Frimpong et al. 2021; Ouattara et al. 2021; Lehmann et al. 2006).

Despite these potential benefits, adoption of compost and biochar by Ghanaian cocoa farmers remains limited (Amponsah-Doku et al. 2022), largely because of obstacles to obtaining high-quality amendments, limited understanding of their use, and a perception of complexity in integrating these technologies into cocoa farming systems. Moreover, little research has directly compared the relative merits of mineral fertilizer, compost and biochar for enhancing soil fertility and cocoa yield in Ghana's cocoa landscapes, particularly when applied under different shade regimes. Addressing soil fertility decline and low cocoa productivity therefore requires soil management strategies that integrate organic and inorganic amendments: mineral fertilizers provide readily available nutrients to support plant growth, while compost and biochar improve soil structure, enhance nutrient retention and promote microbial activity (Bekchanova et al. 2024; Liu et al. 2022; FAO 2006). By integrating mineral fertilizers with organic nutrient sources, cocoa farmers can potentially optimize nutrient use efficiency, improve soil health and increase yield while reducing both environmental impact and production cost. However, empirical evidence on the efficacy of this integrated approach under different agroecological conditions and under contrasting shade regimes remains scarce.

Understanding the combined effects of mineral fertilizer and organic nutrient sources on soil fertility and cocoa yield under different shading regimes is therefore important for developing evidence-based recommendations that support sustainable cocoa production in Ghana. The main objective of this study was to investigate the effect of combined mineral fertilizer and compost/biochar application, under shade and no-shade, on cocoa yield in Ghana's cocoa landscapes. Specifically, the study assessed: (i) the effect of the combined application of mineral fertilizer and compost/biochar under shade and no-shade on cocoa pod production and bean yield; (ii) the associated changes in soil chemical fertility and microbial biomass carbon; and (iii) the cost-effectiveness of integrating mineral fertilizer with compost/biochar. We hypothesized that (i) the combined application of mineral fertilizer and compost/biochar would result in higher cocoa yields than mineral fertilizer or no amendment alone, and (ii) economic returns from cocoa production would be maximized under the integrated use of mineral fertilizer and compost/biochar.

2 Materials and methods

2.1 Study site

The study was conducted in two distinct agroecological zones: the moist semi-deciduous and dry semi-deciduous zones located in the Adansi North District and Offinso Municipality, respectively, both situated within the Ashanti Region of Ghana (Fig. 1). A detailed description of the site can be found in Anokye et al. (2024).

2.2 Experimental design and treatments

Procedures for site selection and plot establishment are detailed in Anokye et al. (2024). The study employed a two-factor split-plot design: shading system as the main-plot factor and soil amendment as

the sub-plot factor, each replicated three times. Two shading systems were used: (i) no shade/full sun and (ii) medium shade. Five soil amendment strategies were applied as sub-plots: (i) no amendment (T1); (ii) mineral fertilizer alone at 90-100-120 kg N-P-K ha⁻¹ (T2); (iii) mineral fertilizer + biochar at 5 t ha⁻¹ (T3); (iv) half-rate mineral fertilizer (45-50-60 kg N-P-K ha⁻¹) + compost without rock phosphate at 5 t ha⁻¹ (T4); and (v) half-rate mineral fertilizer + compost with rock phosphate at 5 t ha⁻¹ (T5).

2.3 Preparation of soil amendments and soil sampling

Biochar was produced on-site by pyrolysis of cocoa pod husk and cocoa litter at 500–600°C using a small-scale pyrolysis reactor developed by an engineer at the Soil Research Institute of Ghana. Compost was produced by combining cocoa pod husk, cocoa litter and poultry manure at a 3:1:1 ratio. Cocoa pod husk and litter were sourced from local farmers' fields, and poultry manure was obtained from nearby poultry farms within the study areas. Soil sampling followed the procedure described in Anokye et al. (2024).

2.4 Laboratory analyses

Standard laboratory procedures, as described in Anokye et al. (2024), were used to characterize the chemical properties of the compost, biochar and their constituent materials (Supplementary Table 1) and the initial physical and chemical properties of the soils in the two ecological zones (Supplementary Tables 2–4).

2.5 Soil microbial biomass carbon, nitrogen and phosphorus

Soil microbial biomass carbon (MBC), nitrogen (MBN) and phosphorus (MBP) were determined by the chloroform fumigation–extraction method (Brookes et al. 1985; Vance et al. 1987), following the detailed extraction and digestion procedure described in Anokye et al. (2024).

2.6 Soil nutrient release

The release of nitrogen, phosphorus and potassium from the soil amendments over the course of each growing season was monitored following the procedure described in Anokye et al. (2024).

2.7 Determination of cocoa yield

Five cocoa trees were tagged in each plot for yield determination. The total number of ripe pods, ripe healthy pods, ripe but rotten pods, and pods lost to rodents were recorded monthly. These data were used to determine the number of pods that reached maturity on the tagged trees, and the monthly totals were summed at the end of each growing season (12 months) to obtain the annual pod load per tree. The percentage of healthy or diseased pods was calculated as:

$$\text{Healthy/diseased pods (\%)} = [(number\ of\ healthy/diseased\ pods) / (total\ pod\ load)] \times 100.... (1)$$

Annual dry bean yield (kg ha^{-1}) was estimated from the total number of healthy, usable pods divided by the pod index, i.e. the number of pods required to obtain 1 kg of dry cocoa beans, estimated from the dry weight of a sample of 30 pods per variety (Ofori and Padi 2020; Padi et al. 2012):

Bean yield (kg ha^{-1}) = (total number of pods) / (pod index) (2)

2.8 Nutrient use efficiency

Nitrogen, phosphorus and potassium use efficiencies (NUE, PUE and KUE, respectively) were calculated for each amended plot as the proportional increase in nutrient uptake (or yield-equivalent nutrient recovery) relative to the unamended control, expressed per unit of nutrient applied, following standard agronomic efficiency conventions (Dobermann 2007).

2.9 Estimation of net income

The cost of all activities, including fertilizer, labour and transportation of materials for each treatment, was calculated as the production cost. Cocoa bean yield ($\text{kg ha}^{-1} \text{ year}^{-1}$) was converted to bags (64 kg = 1 bag), and the number of bags for each treatment was multiplied by the prevailing price of a bag of cocoa to obtain the gross income. Net income was calculated as:

Net income (GH¢) = Gross income (GH¢) – Production cost (GH¢) (3)

2.10 Statistical analysis

Data were analyzed in R. Two-way ANOVA followed by Tukey's HSD test was used to determine differences between treatment means (based on three replicates within each ecological zone) for total pod load, bean yield, soil chemical properties and microbial biomass carbon at the end of each growing season. Statistical significance was set at $p < 0.05$. To identify the factors influencing bean yield and their relative importance, a stepwise multiple regression model was fitted, with all measured soil parameters, nutrient release rates and nutrient use efficiencies included as candidate explanatory variables. The stepwise selection procedure was used to identify the subset of variables best explaining variation in bean yield, and model significance was tested at $p < 0.05$.

3 Results

3.1 Effect of shade and soil amendment on pod load, cherelle wilt, and healthy and diseased pods

Shade system did not significantly affect total pod load in either eco-zone during either growing season ($p > 0.05$; Table 1). In the moist eco-zone, however, plots treated with T2, T3, T4 and T5 recorded significantly ($p < 0.05$) greater total pod loads than untreated (T1) plots in both seasons, and pod load in the amended plots rose further from the first to the second season (e.g. T3, T4 and T5 increased from 52.10, 51.05 and 53.55 pods $\text{tree}^{-1} \text{ year}^{-1}$ to 58.90, 56.50 and 60.90 pods $\text{tree}^{-1} \text{ year}^{-1}$, respectively). On average, 61.4% and 63.6% of the total pod load developed into mature, healthy pods in years 1 and 2, respectively, while the remainder was lost to cherelle wilt and disease. The dry eco-zone mirrored this

pattern, with T2, T3, T4 and T5 consistently recording higher pod loads than T1, marginal increases between the first and second years, and a greater proportion of pods developing into mature, healthy pods in both years.

Table 1

Effect of shade system and soil amendment on pod load ($\text{tree}^{-1} \text{ year}^{-1}$) and on the percentage of healthy and cherelle-wilt/diseased pods in the moist and dry semi-deciduous zones of Ghana. Values are means $\pm$ SEM of three replicates

Shade system	Moist eco-zone					
	Year 1 (2022/2023)			Year 2 (2023/2024)		
Total pod load	Healthy pods	Cherelle wilt + disease pods		Total pod load	Healthy pods	Cherelle wilt + disease pods
(tree ⁻¹ year ⁻¹)	(%)			(tree ⁻¹ year ⁻¹)	(%)	
No shade	48.69 ± 2.99 ^a	61.6	38.4		52.80 ± 2.27 ^a	63.0
Medium shade	50.02 ± 2.93 ^a	61.1	38.9		53.30 ± 2.05 ^a	64.3
Amendment						
T1	35.99 ± 1.20 ^b	58.6	41.4		34.30 ± 0.67 ^b	59.0
T2	54.06 ± 1.46 ^a	61.8	38.2		54.70 ± 0.98 ^a	64.5
T3	52.10 ± 3.62 ^a	61.6	38.4		58.90 ± 2.44 ^a	64.7
T4	51.05 ± 1.37 ^a	62.1	37.9		56.50 ± 1.99 ^a	64.9
T5	53.55 ± 3.46 ^a	62.7	37.3		60.90 ± 2.98 ^a	65.1
System * Amendment (p-value)	0.96			0.98		
Shade system	Dry eco-zone					
	Year 1 (2022/2023)			Year 2 (2023/2024)		
No shade	49.25 ± 2.84 ^a	62.0	38.0	54.47 ± 2.09 ^a		62.2
T1 = no amendment; T2 = mineral fertilizer alone; T3 = mineral fertilizer + biochar; T4 = ½ mineral fertilizer + compost without rock phosphate; T5 = ½ mineral fertilizer + compost with rock phosphate. Means within a column followed by different letters differ significantly at p < 0.05						

Shade system	Moist eco-zone					
	Year 1 (2022/2023)			Year 2 (2023/2024)		
Total pod load	Healthy pods	Cherelle wilt + disease pods		Total pod load	Healthy pods	Cherelle wilt + disease pods
(tree ⁻¹ year ⁻¹)	(%)			(tree ⁻¹ year ⁻¹)	(%)	
Medium shade	49.70 ± 3.07 ^a	63.2	36.8	56.20 ± 2.16 ^a	62.3	37.7
Amendment						
T1	35.60 ± 0.85 ^b	59.0	41.0	35.09 ± 0.55 ^b	59.2	40.8
T2	52.63 ± 1.45 ^a	63.1	36.9	59.25 ± 1.45 ^a	61.7	38.3
T3	52.41 ± 1.07 ^a	62.2	37.8	59.52 ± 2.61 ^a	63.9	36.1
T4	52.24 ± 1.99 ^a	64.1	35.9	60.95 ± 2.11 ^a	61.9	38.1
T5	54.50 ± 3.49 ^a	64.6	35.4	61.85 ± 0.92 ^a	64.5	35.5
System * Amendment	0.87			0.9		
(p-value)						
T1 = no amendment; T2 = mineral fertilizer alone; T3 = mineral fertilizer + biochar; T4 = ½ mineral fertilizer + compost without rock phosphate; T5 = ½ mineral fertilizer + compost with rock phosphate. Means within a column followed by different letters differ significantly at p < 0.05						

3.2 Effect of shade and soil amendment on bean yield

As with pod load, annual bean yield did not differ significantly between the no-shade and medium-shade systems in either eco-zone or growing season. Plots treated with T2, T3, T4 and T5, however, produced significantly higher bean yields than untreated plots (T1) in both eco-zones and both growing seasons (Fig. 2). In the moist eco-zone (Fig. 2a), annual bean yields in the first season were 1324, 1270, 1255 and 1314 kg ha⁻¹ year⁻¹ in the T2, T3, T4 and T5 plots, respectively, increases of 58, 51, 50 and 57% over T1 (836 kg ha⁻¹ year⁻¹). By the second season, these increases had grown to 74, 85, 81 and 93% from T2 (1397 kg ha⁻¹ year⁻¹), T3 (1487 kg ha⁻¹ year⁻¹), T4 (1454 kg ha⁻¹ year⁻¹) and T5 (1549 kg ha⁻¹ year⁻¹), respectively, over T1 (804 kg ha⁻¹ year⁻¹). In the dry eco-zone, bean yields were 833, 1315, 1280, 1328

and 1394 kg ha⁻¹ year⁻¹ in the first season (T1–T5) and 826, 1447, 1507, 1488 and 1563 kg ha⁻¹ year⁻¹ in the second season, representing increases of 58, 54, 59 and 67% in year 1, and 75, 82, 80 and 89% in year 2, from T2–T5 over T1 (Fig. 2b).

a

b

Figure 2 Effect of shade system and soil amendment on cocoa bean yield in (a) the moist and (b) the dry semi-deciduous zones of Ghana, in the first (2022/2023) and second (2023/2024) growing seasons. Error bars = SEM; bars with different letters (uppercase for shade system, lowercase for amendment) differ significantly at $p < 0.05$. T1 = no amendment; T2 = mineral fertilizer alone; T3 = mineral fertilizer + biochar; T4 = ½ mineral fertilizer + compost without rock phosphate; T5 = ½ mineral fertilizer + compost with rock phosphate

A stepwise multiple regression model was used to identify the factors contributing to variation in bean yield (Table 2). Nitrogen, phosphorus and potassium use efficiencies (NUE, PUE, KUE), N and P release, cation exchange capacity (CEC), microbial biomass carbon (MBC), soil N, soil organic matter (SOM) and available P were retained as explanatory variables, jointly accounting for 91% of the variation in bean yield ($R^2 = 0.911$, adjusted $R^2 = 0.891$). Soil N was the strongest single predictor ($p = 0.003$), with a 1% increase in soil N associated with an 810 kg ha⁻¹ year⁻¹ increase in bean yield. Available P, CEC, PUE and KUE were also significant contributors ($p < 0.05$), while N release, P release, MBC and SOM did not reach statistical significance in the final model ($p > 0.05$), despite MBC and soil N both increasing substantially under the organic amendments.

Table 2

Stepwise multiple regression model for cocoa bean yield ($\text{kg ha}^{-1} \text{ year}^{-1}$) as a function of nutrient use efficiencies, nutrient release and soil fertility parameters

Source	Coefficients	Standard Error	t Stat	p-value	R ²	Adj. R ²
Constant	891	108.79	8.19	0.000	0.911	0.891
NUE	3.45	0.69	5.00	0.000		
PUE	-9.33	2.34	-3.99	0.000		
KUE	-1.24	0.57	-2.19	0.034		
N release	-27.60	33.23	-0.83	0.411		
P release	13.97	22.85	0.61	0.544		
CEC	9.38	2.87	3.27	0.002		
MBC	0.45	1.80	0.25	0.805		
Soil N	809.75	260.33	3.11	0.003		
SOM	-45.38	26.02	-1.74	0.088		
Available P	19.24	4.06	4.73	0.000		

NUE, PUE, KUE = nitrogen, phosphorus and potassium use efficiency; CEC = cation exchange capacity; MBC = microbial biomass carbon; SOM = soil organic matter. Model: Yield = 891 + 3.45×NUE - 9.33×PUE - 1.24×KUE - 27.6×N release + 14.0×P release + 9.38×CEC + 0.45×MBC + 810×Soil N - 45.4×SOM + 19.24×Available P

3.3 Effect of soil amendment on soil chemical fertility and microbial biomass carbon

Because soil N, available P, CEC and MBC emerged as key correlates of bean yield in the regression model (Table 2), the underlying soil fertility response to the amendments is summarized in Table 3 for the second growing season (2023/2024); the full shade × amendment breakdown for both seasons is given in Supplementary Tables 5a, 5b and 6. In both eco-zones, soil pH, organic carbon, total N, available P, CEC and MBC all increased significantly ($p < 0.05$) under the amended treatments relative to the unamended control, with the largest gains consistently recorded under T4 and T5. In the moist zone, soil pH rose from 4.56 in T1 to 5.75–5.79 in T4 and T5; organic carbon nearly doubled (1.34% in T1 versus 2.37–2.49% in T4/T5); available P increased roughly three-fold (7.0 to 17.5–19.9 mg kg^{-1}); and MBC increased from 60.2 to 98.3–102.5 mg kg^{-1} . A similar pattern was observed in the dry zone, where MBC rose from 38.4 mg kg^{-1} in T1 to 89.6–94.0 mg kg^{-1} in T4 and T5. T5 (compost + rock phosphate) produced the highest available P and total N in both zones, consistent with the additional P supplied by rock phosphate, while T4 (compost without rock phosphate) produced the highest CEC in the moist zone.

Table 3

Effect of soil amendment on selected soil chemical properties and microbial biomass carbon (MBC) at the end of the second growing season (2023/2024) in the moist and dry semi-deciduous zones of Ghana. Values are means $\pm$ SEM of three replicates, pooled across shade systems

Amendment	Moist semi-deciduous zone					
	pH	SOC (%)	Total N (%)	Avail. P (mg kg ⁻¹)	CEC (cmol(+) kg ⁻¹)	MBC (mg kg ⁻¹)
T1	4.56 $\pm$ 0.18 ^c	1.34 $\pm$ 0.18 ^c	0.21 $\pm$ 0.03 ^c	7.02 $\pm$ 0.80 ^c	5.91 $\pm$ 0.31 ^c	60.15 $\pm$ 0.94 ^d
T2	4.57 $\pm$ 0.04 ^c	1.84 $\pm$ 0.04 ^b	0.37 $\pm$ 0.02 ^b	13.88 $\pm$ 0.86 ^b	8.20 $\pm$ 0.13 ^b	71.11 $\pm$ 2.22 ^c
T3	5.50 $\pm$ 0.29 ^b	2.33 $\pm$ 0.29 ^a	0.41 $\pm$ 0.03 ^{ab}	17.53 $\pm$ 0.93 ^{ab}	9.03 $\pm$ 0.17 ^{ab}	89.39 $\pm$ 3.46 ^b
T4	5.79 $\pm$ 0.22 ^a	2.37 $\pm$ 0.22 ^a	0.41 $\pm$ 0.02 ^{ab}	17.53 $\pm$ 0.82 ^{ab}	9.52 $\pm$ 0.38 ^a	98.30 $\pm$ 2.39 ^a
T5	5.75 $\pm$ 0.23 ^{ab}	2.49 $\pm$ 0.23 ^a	0.46 $\pm$ 0.01 ^a	19.90 $\pm$ 1.57 ^a	9.44 $\pm$ 0.43 ^a	102.54 $\pm$ 4.66 ^a
Dry semi-deciduous zone						
T1	5.82 $\pm$ 0.21 ^b	1.36 $\pm$ 0.21 ^b	0.20 $\pm$ 0.06 ^b	8.79 $\pm$ 0.52 ^c	7.23 $\pm$ 1.55 ^b	38.44 $\pm$ 0.80 ^c
T2	5.83 $\pm$ 0.19 ^b	1.49 $\pm$ 0.19 ^b	0.25 $\pm$ 0.02 ^{ab}	14.71 $\pm$ 0.59 ^b	10.15 $\pm$ 1.52 ^a	52.29 $\pm$ 1.63 ^b
T3	6.48 $\pm$ 0.20 ^a	1.98 $\pm$ 0.20 ^a	0.31 $\pm$ 0.02 ^{ab}	18.36 $\pm$ 1.25 ^a	10.35 $\pm$ 1.59 ^a	72.33 $\pm$ 1.50 ^b
T4	6.55 $\pm$ 0.14 ^a	2.09 $\pm$ 0.14 ^a	0.33 $\pm$ 0.01 ^{ab}	19.53 $\pm$ 1.00 ^a	10.32 $\pm$ 1.55 ^a	89.59 $\pm$ 1.36 ^a
T5	6.53 $\pm$ 0.13 ^a	2.22 $\pm$ 0.13 ^a	0.38 $\pm$ 0.01 ^a	21.39 $\pm$ 0.99 ^a	11.16 $\pm$ 1.65 ^a	93.96 $\pm$ 1.53 ^a

T1 = no amendment; T2 = mineral fertilizer alone; T3 = mineral fertilizer + biochar; T4 = ½ mineral fertilizer + compost without rock phosphate; T5 = ½ mineral fertilizer + compost with rock phosphate; SOC = soil organic carbon; CEC = cation exchange capacity. Means within a column (within zone) followed by different letters differ significantly at $p < 0.05$. Shade system and shade $\times$ amendment effects, and first-season values, are given in Supplementary Tables 5a, 5b and 6

3.4 Nutrient release and nutrient use efficiency

Nitrogen, phosphorus and potassium release from the amendments followed the same general ranking as the chemical fertility indicators, with release consistently greatest under T5 and T4 and lowest under

T1 across both eco-zones and seasons (Supplementary Figs. 1–3). Nutrient use efficiencies showed a less consistent ranking: PUE and KUE were generally highest under medium shade and under T5, whereas NUE did not differ significantly among amendments in most season × zone combinations (Supplementary Table 7). This pattern- strong, consistent amendment effects on nutrient release and soil fertility build-up, alongside weaker and more variable effects on instantaneous nutrient use efficiency- is consistent with the regression result that CEC, soil N and available P, rather than NUE alone, were the dominant predictors of bean yield (Table 2).

3.5 Cost of amendments and return on investment

The cost of the soil amendments was GH¢ 3,670, 5,270, 2,335 and 2,485 for T2, T3, T4 and T5, respectively. In the moist eco-zone, net income at the end of the first season was highest in T5 (GH¢ 25,848), followed by T2 (GH¢ 24,879), T4 (GH¢ 24,726) and T3 (GH¢ 22,114), with T1 lowest (GH¢ 18,026). By the end of the second season, net income followed the ascending order T1 (GH¢ 17,336) < T2 (GH¢ 26,453) < T3 (GH¢ 27,993) < T4 (GH¢ 29,017) < T5 (GH¢ 30,915). Net income increased from the first to the second season under all amendments, with increases over T1 of 38, 23, 37 and 43% for T2, T3, T4 and T5, respectively, at the end of the first season, rising to 53, 62, 67 and 78% by the end of the second season. This trend was mirrored in the dry eco-zone (Fig. 3).

4 Discussion

4.1 Pod load and bean yield response to shade and soil amendment

The absence of a significant shade effect on pod load or bean yield in either eco-zone suggests that, at the moderate shade intensity used in this study, light availability was not a limiting factor for pod set or bean filling relative to the full-sun system. This is consistent with reports that cocoa can tolerate a range of shade intensities without yield penalty provided that soil fertility and nutrient supply are adequately managed, and that yield responses to shade are often secondary to nutrient and water availability (Armengot et al. 2016; Asare et al. 2016; Tschardt et al. 2011). The much larger and highly significant amendment effect, by contrast, points to soil fertility as the dominant constraint on productivity in both landscapes prior to amendment, consistent with the wider literature identifying nutrient depletion as a principal driver of the Ghanaian cocoa yield gap (Kenfack Essougong et al. 2020; Wessel and Quist-Wessel 2015).

The consistently superior performance of T5 (half-rate mineral fertilizer plus compost with rock phosphate) over T2 (full-rate mineral fertilizer alone) in both pod load and bean yield, despite T5 supplying only half the mineral fertilizer rate, indicates that compost amended with rock phosphate can substitute for a substantial share of mineral P and N inputs without compromising yield. This is consistent with evidence that combining organic amendments with reduced mineral fertilizer rates can match or exceed the yield obtained from mineral fertilizer alone, through improved nutrient synchrony,

slower and more sustained nutrient release, and co-benefits for soil structure and microbial activity (Arthur et al. 2024; Kotaix et al. 2023; Asitoakor et al. 2022; Fungenzi et al. 2021; Schroth et al. 2016). The marginally lower performance of T3 (mineral fertilizer plus biochar) relative to T4 and T5 in several comparisons may reflect biochar's comparatively slow and often nutrient-poor direct contribution relative to compost, with its principal benefits, improved cation exchange capacity, water retention and habitat for microbial communities — accruing more gradually over time (Hassan et al. 2023; Khan et al. 2022; Lehmann et al. 2006;); the narrowing gap between T3 and the compost-based treatments from year 1 to year 2 is consistent with this slower-acting mechanism.

4.2 Soil fertility, microbial biomass carbon and nutrient use efficiency as drivers of yield

The regression model (Table 2) identifying soil N, available P and CEC as leading predictors of bean yield, together with the parallel increases in these same properties under the organic amendments (Table 3), provides a coherent mechanistic account of the yield results: amendments that build soil nitrogen, phosphorus availability and cation exchange capacity translate directly into higher bean yield. The near doubling of MBC under T4 and T5 relative to the control in both eco-zones further suggests that compost-based amendments stimulated microbial biomass build-up, consistent with the general role of labile organic inputs in supporting soil microbial communities that, in turn, mediate nutrient cycling and availability to the crop (Frimpong et al. 2021; Ouattara et al. 2021). Although MBC itself was not retained as a significant term in the final regression model once CEC, soil N and available P were accounted for, its strong treatment response and well-documented role as an early indicator of soil fertility recovery (Bekchanova et al. 2024; Liu et al. 2022) suggest that it is better interpreted as part of the causal pathway linking organic amendment to improved nutrient availability, rather than as an independent yield driver in its own right.

The comparatively modest and inconsistent contribution of NUE to the regression model, despite the much clearer amendment effects on nutrient release and soil fertility indicators, suggests that instantaneous nutrient use efficiency is a less reliable predictor of cumulative yield response than the underlying soil fertility status itself, at least over the two-season timeframe of this study. This is plausible given that nutrient use efficiency is itself influenced by seasonal rainfall distribution and plant nutrient demand at the time of measurement, whereas cumulative soil fertility indicators such as CEC and total N integrate the effects of amendment inputs over a longer period (Chianu et al. 2012; FAO 2006).

4.3 Economic returns and implications for smallholder adoption

The finding that T5 produced the highest net income in both seasons and both eco-zones, despite a lower amendment cost than T3 and a lower mineral fertilizer requirement than T2, is central to the practical relevance of this study. For resource-constrained smallholder cocoa farmers, for whom the cost and availability of mineral fertilizer is a well-documented barrier to adoption (Nunoo 2014; Chianu et al. 2012), a strategy that reduces mineral fertilizer requirements by half while increasing both yield and net

income represents a substantially more attractive investment proposition than continued reliance on mineral fertilizer alone. The progressive widening of the net income advantage of T4 and T5 over T2 from the first to the second season also suggests that the economic case for compost-based integrated soil fertility management strengthens over time, consistent with the cumulative build-up of soil organic matter, CEC and microbial biomass, and with broader evidence that returns to organic soil amendment in tree-crop systems tend to be realized over several growing seasons rather than immediately (Gockowski and Sonwa 2011; Wade et al. 2010; Ahenkorah et al. 1987). These results align with calls for wider promotion of on-farm compost production, using cocoa pod husk, cocoa litter and locally available manure, as used in this study, as a low-cost, locally available complement to mineral fertilizer in Ghanaian cocoa landscapes (Zhou et al. 2022; Dogbatse et al. 2021; Muthmainnah et al. 2021; Akinmutimi and Azubuiké 2019; Gule et al. 2019; van Vliet et al. 2015).

4 Conclusion

Integrating mineral fertilizer with compost and biochar significantly increased cocoa pod load, bean yield, soil chemical fertility and microbial biomass carbon relative to an unamended control, in both moist and dry semi-deciduous zones of Ghana, regardless of shade system. Soil nitrogen, available phosphorus and cation exchange capacity were the strongest predictors of bean yield, confirming that the amendments acted principally by rebuilding soil fertility rather than through shade-mediated microclimate effects. Critically, half-rate mineral fertilizer combined with compost and rock phosphate (T5) matched or exceeded the yield and consistently exceeded the net income obtained from full-rate mineral fertilizer alone (T2), while requiring only half the mineral fertilizer input and a comparable or lower amendment cost than biochar (T3). This combination therefore offers smallholder cocoa farmers in Ghana a practical, cost-effective pathway to higher yield and profitability that simultaneously builds long-term soil fertility and reduces dependence on costly mineral fertilizer.

Based on these findings, we recommend that cocoa extension programmes in Ghana promote on-farm production of compost from cocoa pod husk, cocoa litter and locally available manure, combined with half-rate mineral fertilizer and, where accessible, rock phosphate, as an integrated soil fertility management package for both moist and dry semi-deciduous cocoa-growing zones. Because the economic and soil fertility advantages of this package widened between the first and second growing seasons, farmer training and extension messaging should emphasize that the full benefits of compost-based soil fertility management accrue cumulatively and are best realized through sustained, multi-season adoption rather than single-season application. Future research should extend this evaluation across a longer time series, a wider range of shade intensities, and multiple farm sites, and should assess the sensitivity of the yield and soil fertility response to variation in compost and biochar feedstock quality.

Declarations

Conflict of interest:

The authors declare that they have no conflict of interest.

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Author Contribution

JA: conceptualization, methodology, investigation, formal analysis, writing – original draft. AAA, UJ, JSK, VRB, FP: supervision, methodology, writing – review and editing. JTA, SYO, RA, JU: investigation, resources, writing – review and editing. EAG, EN: investigation, data curation. All authors read and approved the final manuscript.

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Data availability

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

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Figures

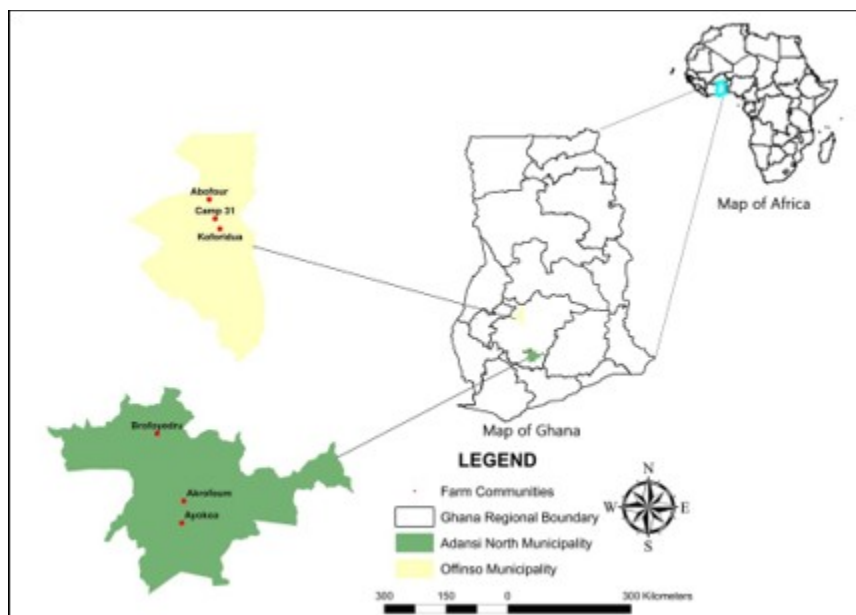
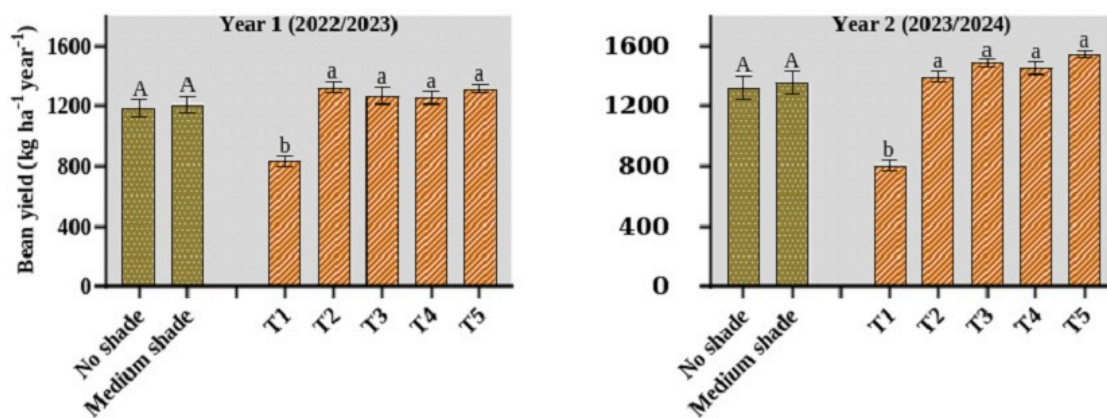
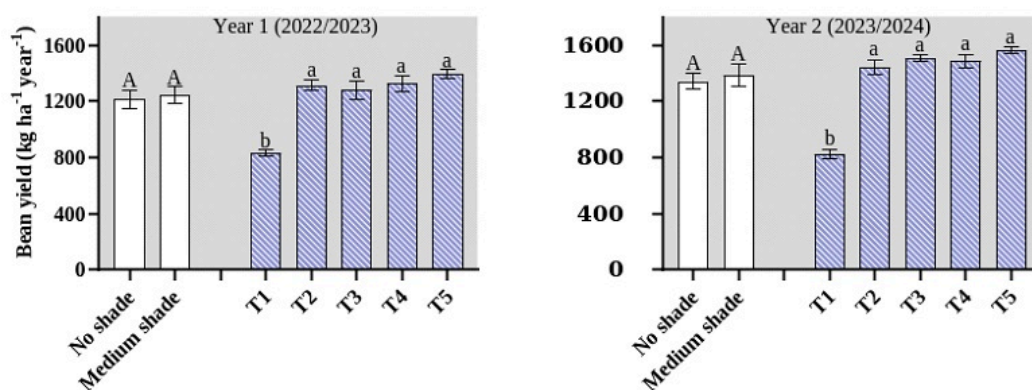


Figure 1

Map showing the study sites and selected farming communities in the moist (Offinso Municipality) and dry (Adansi North District) semi-deciduous zones of Ghana



a



b

Figure 2

Effect of shade system and soil amendment on cocoa bean yield in (a) the moist and (b) the dry semi-deciduous zones of Ghana, in the first (2022/2023) and second (2023/2024) growing seasons. Error bars = SEM; bars with different letters (uppercase for shade system, lowercase for amendment) differ significantly at $p < 0.05$. T1 = no amendment; T2 = mineral fertilizer alone; T3 = mineral fertilizer + biochar; T4 = $\frac{1}{2}$ mineral fertilizer + compost without rock phosphate; T5 = $\frac{1}{2}$ mineral fertilizer + compost with rock phosphate

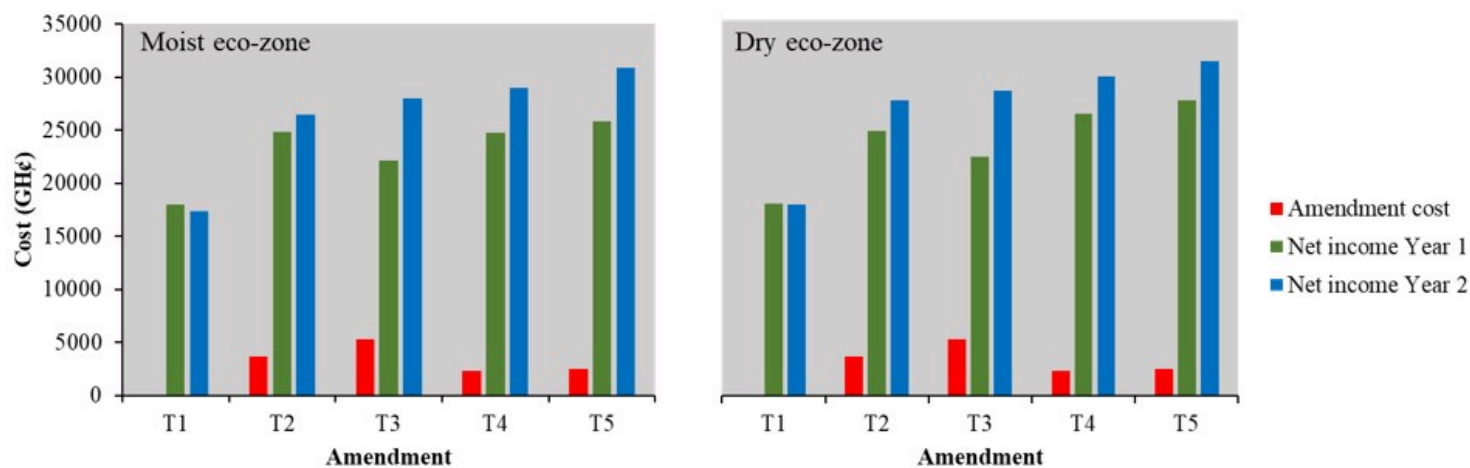


Figure 3

Cost of soil amendment and net income of cocoa production in the moist and dry semi-deciduous zones of Ghana

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