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Enhancing camelina [*Camelina sativa* (L.) Crantz] productivity in acidic Ethiopian soils: Synergistic effects of coffee husk biochar and phosphorus

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Abstract

Acidic soils in Ethiopia's Hadiya Zone limit crop production through aluminum toxicity and phosphorus (P) fixation, which constrain camelina potential. Though drought tolerant, camelina needs sufficient P. Triple superphosphate (TSP) often becomes ineffective because P is rapidly fixed; coffee husk biochar may reduce fixation and improve P availability. Field experiments examined combinations of amendments to test practical options for smallholder farmers in Hadiya, Ethiopia. This study evaluated camelina growth, yield, and P use efficiency under coffee husk biochar and TSP in Hadiya. A split-split-plot design with three replications tested two cultivars (Zeytee-1 and Syria), four TSP rates (0, 23, 46, and 69 kg ha^{-1}), and four biochar rates (0, 10, 12, and 14 t ha^{-1}). Biochar significantly enhanced growth: 14 t ha^{-1} increased leaf area by 48% and plant height by 39%, improving vigor. Combined biochar and TSP maximized yield components; Syria doubled siliques per plant with 69 kg ha^{-1} TSP plus biochar. Peak grain yields reached 2.64 t ha^{-1} for Syria (46 kg ha^{-1} TSP + 12 t ha^{-1} biochar) and 2.60 t ha^{-1} for Zeytee-1 (69 kg ha^{-1} TSP + 14 t ha^{-1} biochar). Biochar raised phosphorus recovery efficiency to 10.8% when combined with 23 kg ha^{-1} TSP. Cultivar responses differed: Zeytee-1 favored higher inputs; Syria performed best with balanced fertilization. Applying 12–14 t ha^{-1} coffee husk biochar with TSP (Zeytee-1: 46–69; Syria: 23–46 kg ha^{-1}) enhances phosphorus efficiency. This practice improves marginal soil productivity and supports camelina as a viable oilseed for acidic soils.

Plain Language Summary

Acidic soils in Ethiopia's Hadiya Zone limit crop production because aluminum toxicity and phosphorus fixation make phosphorus unavailable. This hinders Camelina,

Abbreviations: AE, agronomic efficiency; CEC, cation exchange capacity; HI, harvest index; LAI, leaf area index; LSD, least significant difference; PE, physiological efficiency; PUE, phosphorus use efficiency; RE, recovery efficiency; TSP, triple superphosphate.

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an oilseed with biofuel potential. Researchers tested coffee-husk biochar, applied alone or with triple superphosphate (TSP) fertilizer. Biochar improved Camelina growth; it enhanced root development and plant vigor. Combining biochar with TSP gave the best results, dramatically increasing seed yield and doubling seed-silique numbers in one cultivar. The two cultivars responded differently: Zeytee-1 benefited from higher fertilizer rates, while Syria did best with balanced, moderate doses. Biochar also increased phosphorus-use efficiency. For farmers on acidic soils, applying 12–14 t ha^{-1} of coffee-husk biochar plus moderate TSP is an effective approach to produce camelina and rehabilitate poor soils for this valuable oilseed and support local livelihoods and income.

1 | INTRODUCTION

Agricultural productivity in Ethiopia continues to face significant challenges, particularly in the Hadiya Zone of Central Ethiopia, where acidic soils (pH < 5.5) severely restrict crop yields. Soil acidity in this region leads to aluminum toxicity, phosphorus (P) fixation, and reduced nutrient availability, all of which hinder crop performance (Abure, 2022; Agegnehu et al., 2021; Gemada, 2021; Shetty et al., 2021). Camelina, an emerging oilseed crop valued for its drought tolerance and efficient soil moisture utilization, holds considerable promise for biofuel and edible oil production (Ahmad et al., 2023). In Ethiopia, camelina has recently attracted attention as a climate-resilient alternative to traditional oilseeds such as linseed and rapeseed, with the potential to diversify smallholder farming systems and contribute to national strategies for renewable energy and edible oil self-sufficiency (Manore et al., 2025). However, its productivity in acidic soils is constrained by poor phosphorus availability, a problem further intensified by the strong P-fixation capacity of these soils (Javaid et al., 2021).

Conventional fertilizers such as triple superphosphate (TSP) are often ineffective under acidic conditions because they rapidly transform into insoluble forms, thereby reducing phosphorus availability and agronomic efficiency (AE) (Devasconcelos et al., 2022; Garba, 2022). In contrast, biochar, a carbon-rich material derived from the pyrolysis of organic residues such as coffee husks, has been shown to improve soil pH, enhance cation exchange capacity (CEC), and increase nutrient retention, ultimately boosting fertilizer use efficiency (Mekonnen et al., 2025; Tusar et al., 2023; Zubairu et al., 2023). Studies indicate that biochar-based fertilizers can increase crop yields by up to 94% in acidic tropical soils by enhancing phosphorus availability and reducing leaching losses (Ghassemi-Golezani & Rahimzadeh, 2022; Manore et al., 2024; Zubairu et al., 2023).

Despite these promising findings, limited research has investigated the combined application of coffee husk biochar and TSP in camelina cultivation, particularly under the acidic soil conditions prevalent in Ethiopia. The Hadiya Zone exemplifies this challenge, where strong soil acidity and low phosphorus availability continue to limit camelina productivity (Abure, 2022). TSP application alone often fails to overcome high P-fixation, resulting in suboptimal yields and poor phosphorus use efficiency (PUE) (Ibrahim et al., 2022). While biochar has demonstrated potential in improving soil fertility and phosphorus availability in crops such as potato and maize (Tesfaye et al., 2021), its interaction with TSP in camelina production remains unexplored.

A critical knowledge gap therefore exists regarding the optimal combination of coffee husk biochar and TSP for enhancing camelina yield, cultivar responses, and long-term soil phosphorus dynamics. Addressing this gap is vital for Ethiopian agriculture, where soil acidity and inefficient phosphorus utilization are major constraints to productivity. Coffee husk biochar, an abundant local byproduct, offers a sustainable amendment capable of raising soil pH, improving CEC, and retaining phosphorus in plant-available forms, while TSP supplies readily available phosphorus to support crop growth. Understanding their synergistic effects in camelina cultivation could optimize yields, diversify oilseed production, and contribute to global goals of sustainable agriculture. By improving soil health under acidic conditions, reducing reliance on costly synthetic fertilizers, and promoting circular use of agricultural residues, this research aligns with international priorities for climate-smart farming and long-term food security.

This study therefore aims to evaluate the combined effects of coffee husk biochar and TSP fertilizer on the agronomic performance, yield, and PUE of camelina cultivars in the acidic soils of the Hadiya Zone, Central Ethiopia. Specifically, the objectives are (i) to study the influence of biochar and TSP combinations on growth, yield, and yield components of camelina cultivars; (ii) to evaluate phosphorus use indices, including agronomic and recovery efficiency (RE), under varying application rates; and (iii) to evaluate the effects

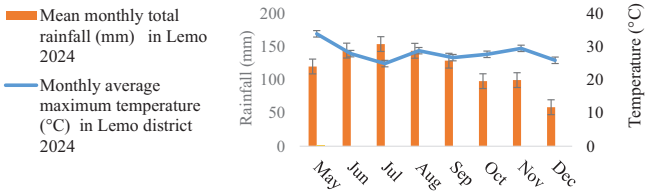


FIGURE 1 Monthly rainfall and temperature during cropping season 2024 (meteorological stations).

of different rates of coffee husk biochar and TSP fertilizer on soil physicochemical properties.

2 | MATERIALS AND METHODS

2.1 | Description of the study area

The experiment was conducted in the Lemo District of the Hadiya Zone, central Ethiopia, situated at approximately 7.67° N latitude and 37.75° E longitude. The district lies about 230 km southwest of Addis Ababa, with elevations ranging from 1700 to 3028 m above sea level. Annual rainfall varied from 1000 to 1400 mm, and mean temperatures ranged from 15°C to 24°C, as shown in Figure 1. Soil conditions are acidic with pH values between 4.5 and 5.5 in the study area (Bekele et al., 2018; Beyene et al., 2023; Niguse & Kassaye, 2018).

2.1.1 | Description of the experimental materials

2.2 | Experimental materials

The study utilized two camelina cultivars, each specifically selected for their adaptability across various agro-ecological conditions (Sido et al., 2023). The first cultivar, Zeytee-1, was registered in 2014 by the Ethiopian Institute of Agricultural Research Center. This small-seeded variety yielded 1.90 t ha^{-1} in farmers' fields and 2.60 t ha^{-1} in controlled research environments (Hailu et al., 2022). The second cultivar, Seria, also featured small seeds and yielded 1.80 t ha^{-1} in farmers' fields and 2.40 t ha^{-1} at research stations.

Coffee husk biochar was produced using a controlled pyrolysis procedure. Fresh coffee husks were air-dried to reduce moisture content and then placed in a sealed metal drum with limited oxygen supply. Pyrolysis was conducted at 350°C–450°C for 2–3 h to allow slow carbonization while preventing complete combustion (Flammini et al., 2020). After cooling naturally under airtight conditions, the resulting biochar was crushed and sieved to a 2-mm particle size before field application. The biochar had a pH of 10.6 and contained 0.9% P, 0.74% Ca, 0.22% Mg, and 4% K. TSP served as the phosphorus fertilizer source.

2.2.1 | Experimental design and treatments

The experiment was conducted using a split-split plot design with three replications to increase the precision of estimating biochar effects under acidic soil conditions. The main plots were assigned to two camelina cultivars selected for their productivity and local adaptability. The subplots received four TSP fertilizer rates (0, 23, 46, and 69 kg ha^{-1}). These rates represented a gradient from no phosphorus input, through low (23 kg ha^{-1}) and moderate (46 kg ha^{-1}) levels consistent with farmer practice and local recommendations, up to a higher rate (69 kg ha^{-1}) intended to assess whether increased application could offset P fixation in acidic soils. Sub-sub-plots were assigned four biochar application rates (0, 10, 12, and 14 t ha^{-1}). The baseline rate of 10 t ha^{-1} was adopted in accordance with the Ethiopian Biochar Consortium recommendation (Amare, 2023; Mekonnen et al., 2025), while the higher rates (12 and 14 t ha^{-1}) were incorporated to assess whether incremental additions improve phosphorus availability and soil fertility. In total, 32 treatment combinations were implemented across 96 experimental plots. Biochar was incorporated into the soil 10 days before sowing. Camelina was drilled on July 26, 2024, at a seed rate of 7.5 kg ha^{-1} with 20 cm row spacing and a seeding depth of 2 cm. Each sub-sub-plot consisted of 18 rows, each 1.2 m long and spaced 0.20 m apart, resulting in a gross plot size of 1.2 × 3.6 m (4.32 m^2). Adequate buffer zones were maintained between adjacent plots and replications to minimize treatment interference.

2.2.2 | Net plot area

For data collection, the outer one row on each side and 0.2 m from both ends of each plot were considered border areas and excluded from sampling. The central 14 rows over a length of 0.8 m were used as the net plot for yield and yield component measurements, giving a net harvested area of 0.8 × 2.8 m (2.24 m^2). Plant samples for growth, phenology, and yield components were taken from this net plot area to ensure uniformity and to avoid edge effects.

2.3 | Soil sampling and analysis

Before sowing, baseline soil samples were collected from the experiment area at a depth of 0–20 cm using a zigzag approach across 10 points. In this method, the sampler moves diagonally across the plot, taking cores at regular intervals to capture variability in soil properties. The 10 cores were

then combined into a composite sample, ensuring representativeness and minimizing localized bias. After harvest, soil samples were collected again from each plot and adjusted to reflect the specific treatments applied. All samples were analyzed at Wachamo University, where texture was determined using the Bouyoucos method (Dzokou et al., 2025), pH was measured potentiometrically (Mosley et al., 2024), organic carbon was assessed following Ma et al. (2024), total nitrogen was analyzed using the Kjeldahl method (Ameer et al., 2024), available phosphorus was determined using the Olsen method (Liu et al., 2024), and CEC was measured according to Antonangelo et al. (2024).

2.4 | Data collection and measurements

2.4.1 | Phenological data

Days to 50% flowering: Number of days when 50% of the plants have opened the flower in each plot.

Note that 90% physiological maturity is the number of days when 90% of siliques change color from green to yellowish or brown.

2.4.2 | Plant growth attributes

Plant height was recorded before flowering from five randomly selected plants in the middle rows of each plot, measured in the field without destructive sampling. Branch number was counted at physiological maturity from five randomly selected plants. Leaf area was measured pre-flowering using a digital leaf area meter (Shi & Wang, 2024), and leaf area index (LAI) was calculated as the ratio of leaf area to ground area.

2.4.3 | Harvesting and data collection for yield components and yield

Shoot fresh biomass was determined at the end of the growth stage from five plants destructively sampled in the main field. Dry biomass was obtained by oven-drying the samples at 75°C for 24 h (Neupane, 2019), and dry matter was calculated using (dry weight/fresh weight) × 100%. The plants in the five central rows were harvested at physiological maturity to determine the number of siliques per plant, seeds per silique, 1000-seed weight, and biological and seed yield. The number of seeds per silique was computed by averaging the count from 10 siliques. Harvested samples were hand-threshed, and seeds were air-dried to 11% moisture content (Duermeyer et al., 2018). Moisture content was measured using a moisture meter. Seed yield per plot was multiplied by plant density to determine seed yield in t ha^{-1}. Note that 1000-seed weight (g) was determined by randomly selecting and weighing 1000 seeds per plot from the sampled plants. Aboveground biomass yield (t ha^{-1}), measured before threshing, was used to estimate biological yield per hectare. The harvest index (HI) was calculated as the percentage ratio of grain yield to above-ground dry biomass.

2.5 | Efficiency indices

Phosphorus uptake in the camelina grain was analyzed using spectrometer methods. This methodology involved several steps: sample preparation (Ebrahimi et al., 2025), digestion, and quantification via techniques of spectrophotometry (Mogashane et al., 2025). The efficiency indices were calculated by the following procedure (Balcha, 2014; Cristina et al., 2020; Dobermann, 2007; Zhan et al., 2015).

$$\begin{aligned}&\text{P concentration } \left(\text{mg kg}^{-1} \text{ or \% P in grain}\right) : \text{P Conc. } \left(\text{mg kg}^{-1}\right)\\&= \left(\text{grain measured P } \left(\text{mg L}^{-1}\right) \times \text{dilution factor} \times \text{yield}\right)\\&/\text{sample weight (kg)}\end{aligned} \tag{1}$$

$$\text{PUE} = \text{grain yield } \left(\text{kg ha}^{-1}\right) /\text{P rate } \left(\text{kg ha}^{-1}\right) \tag{2}$$

$$\begin{aligned}\text{AE} &= (\text{grain yield at Prate} - \text{grain yield at control})\\&/\text{P rate } \left(\text{kg ha}^{-1}\right)\end{aligned} \tag{3}$$

$$\begin{aligned}\text{RE} &= \left[(\text{P Uptake at P rate} - \text{P uptake at control})\right.\\&\left./\text{P rate } \left(\text{kg ha}^{-1}\right)\right] \times 100\%\end{aligned} \tag{4}$$

$$\begin{aligned}&\text{Physiological efficiency (PE)}\\&= (\text{grain yield at P rate} - \text{grain yield at control})\\&/ (\text{P uptake at P rate} - \text{P uptake at control})\end{aligned} \tag{5}$$

2.6 | Data analysis

Before conducting data analysis, the underlying statistical assumptions were evaluated. Normality was assessed using the Shapiro–Wilk test, and homogeneity of variances was examined using Levene's test. Analysis of variance (ANOVA) and correlation analyses were performed in SAS version 9.34 (SAS, 2023), with cultivar, TSP, and biochar treated as fixed factors, and replication, main-plot error, and sub-plot error treated as random factors, following the procedures of Gómez (2002). Treatment effects were interpreted based on the ANOVA results, and significant differences among means

were separated using Tukey's Honestly Significant Difference at the 5% probability level. Pearson's correlation coefficients were computed for the selected parameters.

3 | RESULTS AND DISCUSSION

3.1 | Effects on growth and phenology

3.1.1 | Effects on days to 50% flowering

Cultivar and TSP interacted significantly to affect flowering time (Tables 1 and 2). Zeytee-1 showed consistent flowering (93.6–95.0 days) at 0–46 kg ha^{-1} TSP but delayed at 69 kg ha^{-1} (98.17 days). In contrast, Syria's flowering rose up to 46 kg ha^{-1} TSP within 103.42 days, only to drop sharply at 69 kg ha^{-1} after 98.17 days, suggesting cultivar-specific phosphorus responses in acidic soils, in line with known phenological variation in camelina (Ghidoli et al., 2024).

3.1.2 | Effect on the dry matter per plant

Both cultivars exhibited similar dry matter patterns: minimal variation at 0–46 kg ha^{-1} TSP but a ~50% increase at 69 kg ha^{-1} TSP (Table 2). Camelina growth in acidic soils is severely restricted by phosphorus availability, with a critical level of 46–69 kg ha^{-1} TSP required for substantial biomass increases, consistent with research on the benefits of phosphorus fertilization (Javaid et al., 2021; Sydor et al., 2022).

3.1.3 | Effects on the branches per plant

Branching reflected dry matter results, increasing at 69 kg ha^{-1} TSP for both cultivars. Zeytee-1 showed a more gradual increase than Syria (Table 2). As branching influences yield potential (Lohaus et al., 2020), these differential responses suggest genetic variation in PUE.

3.1.4 | Effects on the leaf area and index (LAI)

Biochar consistently enhanced leaf area and LAI across all TSP levels. At 0 kg ha^{-1} TSP, leaf area increased from 5.4 cm^2 (no biochar) to 8.0 cm^2 with 14 t ha^{-1} biochar (Table 3). The combination of 69 kg ha^{-1} TSP and 14 t ha^{-1} biochar maximized leaf area (9.03 cm^2) and LAI (4.37), indicating synergistic nutrient uptake (Zanetti et al., 2021). The availability of phosphorus is essential for leaf growth in soils that fix phosphorus and are acidic (J. Li et al., 2023), and achieving an optimal LAI necessitates a balanced combination of TSP (69 kg ha^{-1}) and biochar (12–14 t ha^{-1}) to facilitate photosynthesis (Neupane et al., 2022).

3.1.5 | Effects on the plant height

Biochar alone increased height from 75 to 102.3 cm at 14 t ha^{-1}, likely by improving nutrient uptake and mitigating aluminum toxicity (Shetty et al., 2021). At 69 kg ha^{-1} TSP, height peaked at 104.2 cm (with 12 t ha^{-1} biochar), confirming phosphorus as a key growth limiter in acidic soils (Ghidoli et al., 2023). Maximum height (104.1–104.2 cm) required high TSP (69 kg ha^{-1}) and biochar (12–14 t ha^{-1}), demonstrating their interactive role in enhancing soil fertility (Hazrati et al., 2024).

3.1.6 | Effects on the days to 90% maturity

The maturation process was delayed by up to 8 days, as evidenced by the comparison of 0 kg ha^{-1} TSP, in which growth lasted 100 days as opposed to 108 days (Table 3), which may have been caused by extended nutrient release and continued vegetative growth (Hazrati et al., 2024). Higher TSP levels extended the maturity period (e.g., 98 days at 46 kg ha^{-1} TSP+0 t ha^{-1} biochar compared to 108 days at 69 kg ha^{-1} TSP+0 t ha^{-1} biochar). These results contrast with findings from Erskine et al. (2023), potentially reflecting genotype-specific responses to maturity. A combination of 69 kg ha^{-1} TSP and 10–14 t ha^{-1} biochar led to a consistent maturity period of 107–108 days. This implies that biochar prolongs the growing period, possibly because it slowly releases fixed nutrients, whereas TSP accelerates reproductive development at optimal rates (Esmaeili et al., 2024).

3.2 | Effects on the yield and yield components

3.2.1 | Effects on the siliques per plant

Biochar application resulted in a significant and consistent increase in silique production across all cultivars and TSP levels (Table 4). In Syria, a silage count of 88 was achieved at a rate of 69 kg TSP per hectare, combined with 1 t of biochar per hectare, indicating a synergistic effect between high phosphorus levels and biochar to boost reproductive growth (Hazrati et al., 2022; Manzoor et al., 2022).

3.2.2 | Effects on the total biomass

The 3 interaction methods demonstrate significant variations in biomass, as shown in Table 4. Biochar application signif-

TABLE 1 Analysis of variance (ANOVA) summary of cultivar, triple superphosphate (TSP), and biochar rates, and their interaction effects on plant growth and yield components.

		Parameters											
Sources	**DF**	**Dry matter (%)**	**50% Flowering**	**No. of branch**	**Leaf area (cm^2)**	**Leaf area index**	**Height (cm)**	**90% to maturity**	**Siliques per plant**	**Total biomass (t ha^{-1})**	**Grain yield (t ha^{-1})**	**1000-Seed weight (gm)**	**Harvest index**
Cultivars (main plot)	1	NS	***	NS	*	NS	*	NS	NS	**	***	*	NS
TSP rate (kg ha^{-1}) (sub plot)	3	***	***	***	***	***	NS	***	***	***	***	***	***
Biochar rate (t ha^{-1}) (sub-sub plot)	3	***	***	***	***	***	**	***	***	***	***	***	NS
Cultivar × TSP rate	3	***	***	***	***	*	***	*	NS	***	***	***	NS
Cultivar × biochar rate	3	NS	NS	*	NS	NS	***	NS	*	*	***	***	NS
TSP rate × biochar rate	9	*	NS	*	***	***	***	***	***	***	***	***	***
Cultivar × TSP × biochar	9	NS	*	*	NS	NS	NS	NS	**	***	***	***	***

Note: Significance levels are denoted as ***$p < 0.001$, **$p < 0.01$, and *$p < 0.05$, and NS for non-significant results.
Abbreviation: DF, degrees of freedom.

TABLE 2 Interaction effects of cultivar and triple superphosphate (TSP) application rates on phenology, growth, and biomass accumulation in camelina.

		Parameters		
		Days to 90% flowering	Dry matter (%)	Number of branches per plant
Cultivars	TSP (kg ha^{-1})			
Zeytee-1	0	93.6f	3.7b	5.97c
	23	94.2ef	3.82b	7.3b
	46	95.0e	3.9b	7.43b
	69	98.17c	4.86a	8.16a
Syria	0	97.00d	3.9b	7.2b
	23	101.2b	3.92b	7.32b
	46	103.42a	3.69b	7.6b
	69	98.17c	4.85a	8.5a
LSD (0.01%)		0.7	0.42	0.48
CV (%)		0.9	10.8	3.74

Note: Values within a column followed by the same letter do not differ significantly at the $p < 0.01$ level.
Abbreviations: CV, coefficient of variation; LSD, least significant difference.

icantly increased biomass, yielding the highest value of 7.56 t ha^{-1} in the Zeytee-1 treatment with 69 kg ha^{-1} and 14 t ha^{-1} biochar. This result corresponds with the findings of Haghaninia et al. (2023), which show that biochar improves soil structure, enhances water retention, and increases nutrient availability in acidic soils.

3.2.3 | Effects on the grain yield

There is significant variation in camelina grain yield due to three-way interactions, as shown in Tables 1 and 4. The highest yield of 2.64 t ha^{-1} was recorded in Syria with a combination of 69 kg TSP ha^{-1} and 12 t biochar ha^{-1}. The rise is likely due to biochar's ability to lower soil acidity and increase phosphorus accessibility (Agu et al., 2022; Johnson et al., 2007; Nogués et al., 2023). Zeytee-1 displayed a substantial 44% increase in yield when combined with high levels of TSP (69 kg ha^{-1}) and biochar (14 t ha^{-1}), indicating a strong ability to adapt to acidic soils with biochar amendment. Syria achieved optimal results with the application of 46 kg ha^{-1} of TSP and 12–14 t ha^{-1} of biochar, as noted by Erskine et al. in 2023 (Erskine et al., 2023), who found that combining biochar with 46–69 kg ha^{-1} of TSP maximizes yields for camelina in acidic soils, particularly with Zeytee-1 in high-input systems and Syria in balanced nutrient management.

3.2.4 | Effects on the 1000-seed weight

The application of TSP without biochar had a negligible effect, but when applied alongside biochar, it led to a significant rise in seed weight, with Zeytee-1 displaying the most efficient phosphorus uptake when using biochar, which reduces P-fixation in acidic soils (Ahmed et al., 2024; Baninajarian & Shirvani, 2020; Zwetsloot et al., 2016).

3.2.5 | Effects on the HI

Zeytee-1 exhibited moderate HI values ranging from 0.40 to 0.46, with the maximum (0.46) recorded under 69 kg ha^{-1} TSP combined with 10 t ha^{-1} biochar. In contrast, Syria showed a wider HI range (0.33–0.47), achieving its peak value (0.47) at 23 kg ha^{-1} TSP with 14 t ha^{-1} biochar, highlighting its strong responsiveness to nutrient supply and soil amendment strategies (Palansooriya et al., 2019). Previous studies support these findings: Jemal and Yakob (2021) demonstrated that biochar improves soil pH and nutrient retention in acidic soils, thereby enhancing camelina yield and HI; Hazrati et al. (2024) reported that camelina's adaptability to marginal soils is reinforced by organic amendments such as biochar, which mitigate aluminum toxicity, and George et al. (2017) emphasized that biochar's benefits are most pronounced in low-fertility acidic soils, reducing the need for high TSP inputs (Jindo et al., 2020).

3.3 | Soil properties

3.3.1 | Effects on the physical properties

Biochar application (0–14 t ha^{-1}) did not change sand or clay content, but it improved soil structure by reducing clay

TABLE 3 Interaction effects of triple superphosphate (TSP) and biochar application rates on leaf area, leaf area and index (LAI), plant height, and maturity in camelina.

Parameters					
		Leaf area (cm^2)	Leaf area index (%)	Height per plant	Days to 90% maturity
TSP (kg ha^{-1})	Biochar (t ha^{-1})				
0	0	5.4h	2.41e	75h	100g
	10	6.76g	3.0d	81.7f	104f
	12	7.50f	3.18d	89d	1006e
	14	8.0bcde	3.85ab	102.3c	108a
23	0	7.5f	2.68e	75.1h	99h
	10	7.65def	3.26d	80.0g	100g
	12	7.58ef	3.61c	88.6d	106e
	14	9.95bcdef	3.8abc	103.0bc	108a
46	0	8.2bc	2.68e	78.0gh	98h
	10	7.9bc	3.1d	82.8f	104f
	12	8.20bc	3.78abc	87.5e	106e
	14	8.23ab	3.87abc	103.5b	108a
69	0	8.4b	3.90 ab	89.0d	108a
	10	8.3b	3.83abc	100.2c	107ba
	12	8.8ab	4.2a	104.2a	108a
	14	9.03a	4.37a	104.1a	108a
LSD (0.01%)		0.45	0.27	1.14	0.5
CV (%)		5.23	6.68	1.05	0.42

Note: Values within a column followed by the same letter do not differ significantly at the $p < 0.01$ level.
Abbreviations: CV, coefficient of variation; LSD, least significant difference.

effects through dilution and better aggregation (Acharya et al., 2024). Likewise, TSP application (0–69 kg ha^{-1}) alone produced only minor fluctuations in the measured clay fraction, indicating limited short-term effects on particle-size distribution. However, the combined application of biochar and TSP resulted in a markedly lower measured clay fraction (43%–43.4%). This reduction likely reflects biochar-induced aggregation and dilution effects rather than a true alteration of inherent soil texture, demonstrating that biochar exerts a stronger short-term influence on particle-size measurements (Y. Li et al., 2019) than TSP alone. Biochar is known to improve the structure of clay loam soils by enhancing aeration, drainage, and aggregate stability (Are, 2019).

3.3.2 | Effects on the chemical properties

Soil acidity (pH 5.0; Figure 2) was effectively corrected to near-neutral conditions (pH 6.5) through the combined application of biochar and 46–69 kg ha^{-1} TSP, consistent with earlier findings by Esilaba et al. (2023), Jemal and Yakob (2021), and Tusar et al. (2023). This adjustment in soil reaction created a more favorable environment for nutrient availability and crop growth. Phosphorus levels, initially deficient at 8 mg kg^{-1}, increased substantially to an adequate range of 85–87 mg kg^{-1} when 69 kg TSP ha^{-1} was applied together with 14 t biochar ha^{-1} (Wali et al., 2022). While TSP supplied the bulk of phosphorus, biochar contributed by reducing fixation and enhancing retention (Xiu et al., 2021). Similarly, CEC improved from 6.5 to 10.9 cmolc kg^{-1} with 14 t ha^{-1} biochar, confirming its role in strengthening nutrient-holding capacity (Esilaba et al., 2023; Kaur et al., 2024).

Nitrogen levels rose from a low 0.12% to a moderate 0.18%–0.22%, with the greatest concentration of N (0.22%) achieved when applying 46–69 kg ha^{-1} TSP and 14 t ha^{-1} biochar (Figure 3) (Sinha et al., 2023). Simultaneously, soil organic carbon rose from 1.2% to an ideal 2.0%–3.0% (Kaur et al., 2024).

3.4 | Efficiency indices

3.4.1 | Effects on phosphorus uptake

Biochar alone (14 t ha^{-1}) modestly increased P uptake from 2.53 to 2.89 kg ha^{-1} without TSP. However, combined with TSP, biochar significantly enhanced uptake. At 46 kg ha^{-1} TSP, P uptake rose from 5.78 kg ha^{-1} (without biochar) to 8.33 kg ha^{-1} (a 44% increase) with biochar. This synergy is most pronounced at intermediate TSP levels (23–46 kg

TABLE 4 Interaction effects of cultivars, triple superphosphate (TSP), and biochar application rates on yield and yield components.

			Parameters				
			Siliques per plant	Total biomass (t ha^{-1})	Grain yield (t ha^{-1})	1000-Seed weight (gm)	Harvest index
Cultivars	TSP (kg ha^{-1})	Biochar (t ha^{-1})					
Zeytee-1	0	0	44^{g}	4.40^{n}	1.60°	1.11^{e}	0.45^{b}
		10	49^{fg}	5.16^{lm}	2.00^{k}	1.2^{d}	0.43^{d}
		12	72de	5.43$^{i\,jklm}$	2.03^{k}	1.3^{b}	0.44bc
		14	72de	5.33^{jklm}	2.30^{h}	1.4^{ab}	0.42def
	23	0	59^{def}	5.193^{klm}	1.93^{l}	1.2^{d}	0.41^{ef}
		10	76^{cd}	5.66$^{ghi\,j}$	2.13^{j}	1.3^{bc}	0.43^{cde}
		12	81^{bc}	5.90^{fgh}	2.31^{h}	1.3^{b}	0.42^{def}
		14	85^{a}	5.76^{ghi}	2.50bc	1.3^{bc}	0.42^{def}
	46	0	57^{def}	5.30^{jklm}	1.90^{l}	1.1^{e}	0.40^{fg}
		10	62^{def}	5.66$^{ghi\,j}$	2.00^{k}	1.23^{cd}	0.42^{def}
		12	77^{cd}	6.20^{def}	2.30^{h}	1.3^{bc}	0.44^{bc}
		14	85^{a}	7.32^{a}	2.40c	1.4^{ab}	0.44bc
	69	0	61def	4.56^{n}	1.89^{l}	1.2^{d}	0.41^{def}
		10	83^{ab}	5.06^{m}	2.20^{i}	1.8^{A}	0.46^{ab}
		12	84^{ab}	7.00ab	2.63a	1.73^{A}	0.43^{cd}
		14	88^{a}	7.56a	2.6a	1.90^{A}	0.41^{def}
Syria	0	0	62^{def}	5.60$^{ghi\,jk}$	1.70^{n}	1.10^{e}	0.33^{i}
		10	61^{def}	5.53$^{hi\,jkl}$	2.03^{k}	1.2^{d}	0.42^{def}
		12	78^{cd}	5.60$^{ghi\,jk}$	2.10^{j}	1.3^{bc}	0.43^{cd}
		14	77^{cd}	5.80^{fghi}	2.30^{h}	1.4^{ab}	0.43^{cde}
	23	0	53^{ef}	5.40$^{i\,jklm}$	1.80^{m}	1.20^{d}	0.36^{hi}
		10	61^{def}	6.66^{bc}	2.30^{h}	1.22^{d}	0.38^{gh}
		12	77^{cd}	6.46^{bcd}	2.45^{fg}	1.23^{cd}	0.43^{cde}
		14	80bc	6.33^{cde}	2.62^{a}	1.40^{ab}	0.47^{a}
	46	0	57^{def}	4.40^{n}	2.133^{j}	1.10^{e}	0.46^{a}b
		10	61^{def}	6.46^{bcd}	2.54^{b}	1.22^{cd}	0.46^{ab}
		12	73de	6.73^{bc}	2.55^{b}	1.32^{bc}	0.41^{efg}
		14	88^{a}	6.50^{bcd}	2.44^{bc}	1.40^{ab}	0.45^{ab}
	69	0	84^{ab}	4.63^{n}	2.53^{b}	1.10^{e}	0.43cde
		10	85^{ab}	6.60^{bcd}	2.63^{a}	1.22^{cd}	0.46^{ab}
		12	85^{a}	6.93ab	2.64^{a}	1.32^{bc}	0.45ab
		14	88^{a}	7.07a	2.62a	1.60^{a}	0.45^{ab}
	LSD (0.01%)		7.38	0.42	0.6	0.5	0.036
	CV (%)		5.4	4.47	1.22	3.88	4.86

Note: Values within a column followed by the same letter do not differ significantly at the $p < 0.01$ level.
Abbreviations: CV, coefficient of variation; LSD, least significant difference.

ha^{-1}), primarily due to increased soil pH and reduced aluminum solubility limiting phosphorus binding (Lindsay & Walthall, 2020; Penn & Camberato, 2019). Yuan et al. (2025) similarly found rice straw biochar increased available P by 13.1%–49.1% in acidic soils.

3.4.2 | Effects on the PUE

PUE (kg kg^{-1}) was significantly affected by TSP and biochar rates (Tables 5 and 6). At 23 kg ha^{-1} TSP, biochar raised PUE from 81.1 (0 t ha^{-1}) to 111.4 (14 t ha^{-1}), while the

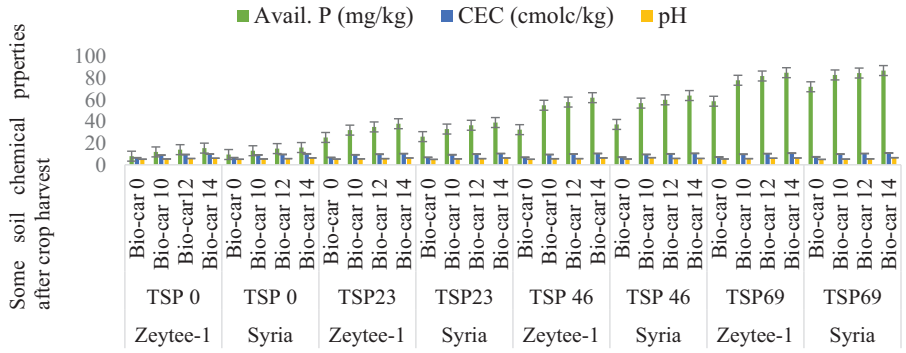


FIGURE 2 Post-harvest soil chemical properties (available P, cation exchange capacity [CEC], and pH) as influenced by camelina cultivars, biochar, and triple superphosphate (TSP) rates.

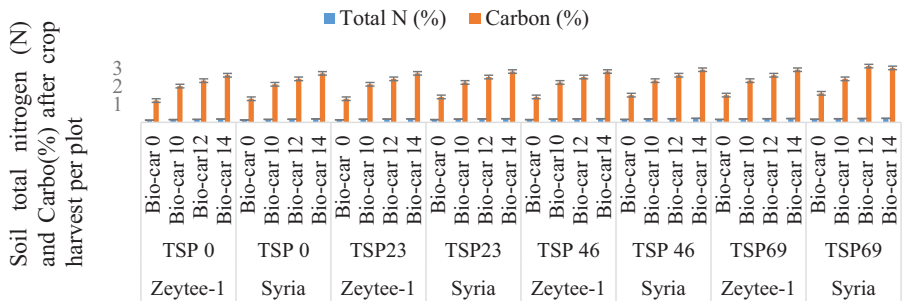


FIGURE 3 Post-harvest soil chemical properties (total N and carbon %) as influenced by camelina cultivars, biochar, and triple superphosphate (TSP) rates.

TABLE 5 Analysis of variance (ANOVA) summary for the main and interaction effects of cultivar, triple superphosphate (TSP), and biochar rates on uptake and use efficiency.

		Parameters				
Source	**DF**	**P uptake (kg ha^{-1}**	**PUE (kg kg^{-1})**	**AE (kg kg^{-1})**	**RE (%)**	**PE (kg kg^{-1})**
Cultivar	1	**	**	NS	**	NS
TSP rate (kg ha^{-1})	2	***	***	***	***	***
Biochar rate (t ha^{-1})	3	***	***	***	*	*
Cultivar × TSP rate	2	**	***	***	***	***
Cultivar × biochar rate	3	*	NS	NS	*	*
TSP rate × biochar rate	6	***	***	***	**	**
Cultivar × TSP rate × biochar rate	6	NS	NS	NS	NS	NS

Note: Significance levels are denoted as ***$p < 0.001$, **$p < 0.01$, and *$p < 0.05$, and NS for non-significant results.
Abbreviations: AE, agronomic efficiency; DF, degrees of freedom; PE, physiological efficiency; PUE, phosphorus use efficiency; RE, recovery efficiency.

effect declined at higher rates, with the optimum (102.8) at 46 kg ha^{-1} TSP and 12 t ha^{-1} biochar. At 69 kg ha^{-1} TSP, PUE generally decreased with biochar. This shows that higher phosphorus uptake did not always improve efficiency, as excess TSP in acidic soils is often fixed by Al and Fe oxides, limiting its productive use. Biochar enhanced PUE mainly at lower rates by raising soil pH, reducing Al toxicity, and improving nutrient retention, consistent with its role in slowing residue mineralization (Pandit, 2018) and improving retention in acidic soils (Asap, 2017). Importantly, improved PUE also reduces leaching and runoff losses, lowering risks of eutrophication and minimizing reliance on synthetic fertilizers, thereby linking AE with environmental sustainability in acidic soils.

TABLE 6 Interaction effects of triple superphosphate (TSP) and biochar application rates on phosphorus uptake and use-efficiency traits.

		Parameters				
		P uptake (kg ha^{-1})	PUE (kg kg^{-1})	AE (kg kg^{-1})	RE (%)	PE (kg kg^{-1})
TSP (kg ha^{-1})	Biochar (t ha^{-1})					
0	0	2.53l	–	–	–	
	10	2.65l	–	–	–	
	12	2.71l	–	–	–	
	14	2.89k	–	–	–	
23	0	4.11j	81.1d	9.42cde	6.88f	0.144bc
	10	4.33i	96.3c	12.31b	7.30ef	0.174b
	12	4.51i	103.6b	16.66a	7.82de	0.217a
	14	4.88h	111.4a	11.44bc	10.8a	0.202a
46	0	5.78j	43.84h	7.97def	8.26cd	0.12 e
	10	6.46f	49.35g	8.28f	10.4f	0.11de
	12	7.1e	102.8b	7.31ef	7.06f	0.13cd
	14	8.33cd	97.7bc	10.32bcd	8.29cd	0.094e
69	0	7.4e	33.50l	9.58de	8.43cd	0.092e
	10	8.6b	45.3g	7.72ef	8.64c	0.078e
	12	8.7a	54.2fg	10.5bc	8.43cd	0.106de
	14	8.8a	37.5k	7.63ef	8.5c	0.090e
LSD (0.01%)		0.22	1.07	1.14	0.67	0.366
CV (%)		3.2	1.38	22.28	6.57	8.45

Note: Values within a column followed by the same letter do not differ significantly at the $p < 0.01$ level.
Abbreviations: AE, agronomic efficiency; CV, coefficient of variation; LSD, least significant difference; PE, physiological efficiency; PUE, phosphorus use efficiency; RE, recovery efficiency.

3.4.3 | Effects on the AE

AE (kg kg^{-1}) response was complex, with the highest value (16.66) observed at 23 kg ha^{-1} TSP and 12 t ha^{-1} biochar. Biochar generally enhanced AE at lower TSP rates but showed inconsistent effects at higher rates (Sessa et al., 2021). This indicates that greater phosphorus uptake did not always translate into higher efficiency, as acidic soils often fix excess phosphorus into unavailable forms, limiting its contribution to yield. Biochar improved AE at moderate inputs by raising soil pH, reducing aluminum toxicity, and enhancing nutrient retention, thereby increasing the proportion of absorbed phosphorus used productively. However, at higher TSP rates, nutrient retention may reach saturation, or uptake may exceed crop demand, leading to diminishing efficiency. This pattern is consistent with findings that Brassica species, including camelina, require suitable moisture and a balanced nutrient supply during critical growth stages for optimal response (Javaid et al., 2021). The reduced positive effects of biochar at higher TSP levels therefore suggest altered phosphorus uptake dynamics or non-productive accumulation (DaSilva Carneiro et al., 2021; Lustosa Filho et al., 2020).

3.4.4 | Effects on the RE

RE was strongly influenced by TSP and biochar interactions. The highest grain RE (10.8%) occurred at 23 kg ha^{-1} TSP with 14 t ha^{-1} biochar, showing that moderate phosphorus supply with biochar maximizes uptake under acidic soil conditions by improving pH and reducing Al fixation (Esmaeili et al., 2024). At higher TSP rates, yields increased but efficiency declined, as excess phosphorus was increasingly immobilized by Al and Fe oxides, reducing the relative benefit per unit input. This was evident at 46 kg ha^{-1} TSP, where RE declined slightly and biochar's positive effect became less pronounced, reflecting diminishing returns in acidic soils (Hazrati et al., 2024).

3.4.5 | Effects on the PE

The highest PE values occurred at 23 kg ha^{-1} TSP with biochar. PE generally decreased with increasing TSP rates, irrespective of biochar application (Table 6). At higher TSP rates (46 and 69 kg ha^{-1}), biochar had minimal effect on PE (Mollick, 2018).

3.5 | Correlation analysis of the yield attributes

The relationships among various growth factors reveal important insights into yield potential (Table 7). A higher LAI correlates with increased biomass accumulation. In addition, extended vegetative growth enhances dry matter, while more branches contribute to greater biomass production. The number of silicles directly impacts grain yield, with later flowering allowing for more silicle formation (Ziaei et al., 2024). Ultimately, higher grain yields originate from silicle count, biological yield, and branching, suggesting that camelina breeding should concentrate on silicle production and biomass for maximum yield enhancement (Ghidoli, 2024).

3.5.1 | Correlation analysis uses indices

Increased phosphorus uptake by crops often reduces P use, agronomic, and physiological efficiencies, suggesting diminishing returns (Veneklaas et al., 2012) (Table 8). Although higher phosphorus uptake can lead to improved recovery, it does not always result in a greater yield per unit of phosphorus (Elser & Haygarth, 2021). Furthermore, increased PUE is associated with enhanced agronomic and physiological efficiencies. Furthermore, strong PE boosts AE, although very high PE might slightly lower P recovery (Wang et al., 2010).

4 | CONCLUSION

Coffee husk biochar significantly improved camelina growth and yield in Hadiya's acidic soils, with 12–14 t ha^{-1} combined with TSP producing the best outcomes. Cultivar responses differed: Zeytee-1 required higher TSP (46–69 kg ha^{-1}), while Syria performed best at lower rates (23–46 kg ha^{-1}). Soil fertility improved markedly, with pH rising from 5.0 to 6.5 and available phosphorus from 8 to 85–87 mg kg^{-1}. For practice, farmers should apply 12–14 t ha^{-1} biochar as a baseline amendment, tailoring TSP rates to cultivar choice—lower inputs for Syria in resource-limited systems and higher inputs for Zeytee-1 in intensive systems. Policy support for biochar use can promote sustainable nutrient management, reduce reliance on imported fertilizers, and recycle local residues.

Future research should examine long-term effects on subsoil acidity, exchangeable aluminum, and economic feasibility while exploring adoption strategies across diverse Ethiopian farming systems.

TABLE 7 Correlation analysis of agronomic traits in Camelina cultivars.

	LAI	Dry matter (%)	Days to 50% flowering	No. of branch	Height	Days to 90% maturity	No. of Siliques	Biological yield (t ha^{-1})	Grain yield (t ha^{-1})	1000-Seed weight
LAI	1									
Dry matter (%)	0.84***	1								
Days to 50% flowering	0.73***	0.87**	1							
No. of branches	0.787**	0.86**	0.73***	1						
Height	0.84***	0.89**	0.76***	0.83***	1					
Days to 90% maturity	0.83***	0.89**	0.84***	0.83***	0.88**	1				
No of siliques	0.45**	0.41**	0.47***	0.49***	0.46**	0.49***	1			
Biological yields	0.78***	0.69**	0.62***	0.64***	0.72**	0.75***	0.64***	1		
Grain yield	0.72***	0.72**	0.53***	0.75***	0.57**	0.56***	0.85**	0.79***	1	
1000-Seed weight	0.31*	0.23^{NS}	0.032^{NS}	0.22^{NS}	0.23^{NS}	0.18^{NS}	−0.33*	0.34*	−0.03^{NS}	1

Note: Significance levels are denoted as ***$p < 0.001$, **$p < 0.01$, and *$p < 0.05$, and NS for non-significant results.
Abbreviation: LAI, leaf area and index.

TABLE 8 Correlation analysis of P uptake and efficiency matrices.

	P uptake (kg ha^{-1})	PUE (kg kg^{-1})	AE (kg kg^{-1})	RE (%)	PE (kg kg^{-1})
P uptake (kg ha^{-1})	**1**				
PUE (kg kg^{-1})	−0.79***	1			
AE (kg kg^{-1})	−0.34**	0.52***	1		
RE (%)	0.59***	−0.19 NS	−0.23 NS	1	
PE (kg kg^{-1})	−0.57***	0.6***	0.82***	−0.42***	1

Note: Significance levels are denoted as ***$p < 0.001$ and **$p < 0.01$, and NS for non-significant results.
Abbreviations: AE, agronomic efficiency; PE, physiological efficiency; PUE, phosphorus use efficiency; RE, recovery efficiency.

AUTHOR CONTRIBUTIONS

Daniel Manore: Conceptualization; data curation; investigation; methodology; writing—original draft. **Shimelis Gizachew**: Methodology; resources; visualization; writing—review and editing. **Tewodros Ayalew**: Conceptualization; methodology; supervision; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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