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Research article

Effects of integrated fertilizer application on selected soil properties and yield attributes of common bean (*Phaseolus vulgaris* L.) on different soil types

Rameto Wabela [a,b,*], Girma Abera [a], Bekele Lemma [c], Amsalu Gobena [a]

[a] *School of Plant and Horticultural Science, Hawassa University, Hawassa, Ethiopia*
[b] *Soil Resource and Watershed Management, Werabe University, Werabe, Ethiopia*
[c] *Department of Chemistry, Hawassa University, Hawassa, Ethiopia*

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ABSTRACT

In Ethiopia, common bean (*Phaseolus vulgaris* L.) productivity remains low because of low soil fertility. However, both plant production and soil fertility benefit from integrated application of fertilizers. Thus, this study investigates the effect of integrated application of inorganic, organic and biofertilizers on selected soil properties and yield components of common bean. A field experiment was conducted at three sites in southern Ethiopia, under two consecutive cropping season (2021 and 2022). The experiment was conducted using a randomized complete block design (RCBD) with three replications. The treatments included three levels of inorganic fertilizer (Triple Superphosphate, TSP), applied at 0, 42.5, and 85 kg TSP ha^{-1} for Kokate; 0, 29, and 58 kg TSP ha^{-1} for Hawassa; and 0, 35.5, and 71 kg TSP ha^{-1} for Alage, tailored to the specific conditions of each site. Additionally, the experiment incorporated three levels of organic inputs 0, 5 t biochar ha^{-1}, and 5 t compost ha^{-1} as well as Rhizobium inoculation (HB-429) applied at 500 g ha^{-1}. These treatments were designed to assess the combined effects of inorganic, organic and biofertilizers on soil health and crop performance. Results showed that the integrated application of inorganic, and organic fertilizers significantly ($p \leq 0.05$) improved soil pH, soil organic carbon, and available P compared with the sole fertilizer application plots. Similarly, the integrated use of inorganic, organic and biofertilizers increased nodule numbers, seed weight, grain yield, and biomass yield. We also found that 23 and 24 % higher grain yield were achieved with integrated applications of TSP fertilizer with compost on Hawassa and Alage sites than sole inorganic fertilizer application. On the other hand, the integrated application of TSP fertilizer with biochar increased by 18 % grain yield on Kokate over the sole application of inorganic fertilizer. The highest economic benefit of 69,460 and 63,250 ETB was obtained from the integrated application of TSP fertilizer with compost at Hawassa and Alage sites, respectively. The highest economic benefit for the Kokate site was 53,583 ETB at TSP fertilizer with biochar application. Overall, the study confirms that site-specific integrated soil fertility management appears to be a prerequisite for sustainable and profitable common bean production over sole fertilizer application in southern Ethiopia.

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* Corresponding author. Tel.: +251-967229631, P.O. Box 46.
E-mail address: ramwab971@gmail.com (R. Wabela).

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1. Introduction

Legumes are a key accelerator of agricultural development and growth in Ethiopia. It improves food or nutrition diversity, enhances the rural economy, enhances soil fertility, and creates more sustainable and climate-resilient food systems due to its ability to fix atmospheric nitrogen (N_2) and a short growth cycle [1,2]. In terms of the proportion of the national area of production, legumes cover around 12 %, of which faba bean (4 %), common bean (2.4 %), chickpea (1.7 %), and field pea (1.69 %) are among the major legume crops [3]. However, key constraints to legume intensification in the country include limited access to high-quality seeds, minimal or no use of fertilizers in legume production, insufficient promotion of appropriate legume technologies, and widespread misconceptions among farmers regarding fertilizer use for legume cultivation [4].

The common bean (*Phaseolus vulgaris* L.) is one of Ethiopia's most important leguminous food crops. It is widely produced by smallholder farmers for home consumption, cash income, and soil fertility improvement, either by sole cropping or rotational and/or intercropping with cereal [5,6]. However, the national actual yield from smallholder farmland has remained low at 1700 kg ha^{-1}, which is significantly below the potential yield of 3500 kg ha^{-1} [7–9]. Several production limiting factors may have contributed to the poor national average yield of common beans. These include soil fertility decline, limited fertilizer use, low rhizobia technologies, and insufficient availability of improved seeds varieties [10,11]. Over 43 % of Ethiopian soils are covered by acidic soils, of which 28 % are categorized as strongly acidic, 4.1–5.5 [12], while about 13 % of Ethiopia's agricultural soils are saline soils. Studies have shown that the nutrient depletion rates of agricultural soils in Ethiopia were 122 kg N, 13 kg P, and 82 kg K ha^{-1} yr^{-1}, and these rates were twice as high as the average rate for Sub-Saharan Africa [13]. Moreover, the average soil organic carbon (SOC) stock in Ethiopia's highlands has been continuously declining over time at -3.7 t ha^{-1} y^{-1} [14]. Therefore, new approaches, including the use of fertilizer formulation and application methods, are required to maintain soil fertility and crop yield [15].

The judicious use of fertilizers, together with key complementary agronomic practices, has been proven to increase overall agricultural productivity and thereby nutrient use efficiency [12,16–19]. Phosphorus (P) is the second most important nutrient after nitrogen (N) for all crops. In particular, P fertilizer is useful for efficient N_2 fixation of legumes, good quality grain production, and immediately releases nutrients that are accessible to plants. Its application sustains crop yield. Due to the high cost of inorganic fertilizer and a lack of soil and crop-specific fertilizer, resource-poor farmers cannot afford a sufficient amount of it, and, as a result, the farmers have resorted to applying low amounts of inorganic N and P fertilizers [20]. Additionally, the continuous use of N and P inorganic fertilizers would primarily enhance the uptake and depletion of micronutrients such as zinc and boron, as well as secondary nutrients such as sulfur [21]. Therefore, continuing to use inorganic N and P fertilizers alone will not be a sustainable solution, as it will result in soil acidity, loss of SOC, and depletion of nutrients [22].

On the other hand, the addition of organic fertilizer could significantly improve soil properties such as soil porosity, available water, SOC, nutrient status, and bulk density [23]. Organic fertilizer can also reduce nutrient losses by adsorbing nutrients from the soil and increasing soil water retention capacity, which improves plant nutrient uptake [24,25]. According to Zhang et al. [26], using organic fertilizers can increase the quantity of macro-aggregates in the soil, improve their stability, improve soil structure, and reduce P and other nutrient losses. Organic fertilizers, rich in humic acid, enhance SOC content and aid in the formation of microscopic aggregates. Biochar can improve SOC storage and bioavailability, promoting microbial growth and the production of enzymes involved in carbon breakdown [27,28]. According to Mukherjee et al. [29], applying biochar can alter phosphatase activity, elevate the amount of accessible P in the soil, release stored P, and decrease P fixation. Brassard et al. [30], the water and nutrient content of biochar promotes microbial activity, improves nitrogen and P use rates, and reduces nutrient leaching loss. Furthermore, the humic compound considerably enhanced accessible P and facilitated plant P uptake. Similarly, Liu et al. [31] discovered that adding humic substances increased the amount of aggregates and microbes in the soil, enhanced maize production, and eliminated nutrients from the root system. However, small-scale farmers cannot afford to add the required amounts of organic fertilizer due to competing uses of crop residue for animal feed and fuel. Moreover, the labor limit significantly reduced the preparation and transport of organic fertilizer, given the bulkiness of organic fertilizer required for an adequate supply of plant nutrients [32,33].

Rhizobia inoculants can assist soil fertility levels through N_2 fixation from the atmosphere and solubilize inorganic P fixed to soils, thereby reducing farmer's dependency on inorganic fertilizers [34]. Therefore, integrated inorganic TSP, organic fertilizers, and biofertilizer applications improve soil properties, enhance crop yield, and release nutrients quickly, thereby enhancing the overall crop yield. However, information on the integrated effects of inorganic, organic, and biofertilizer to understand the impact on soil properties and crop production is limited in the studied areas. Therefore, this study aimed to investigate the effects of the integrated use of inorganic and organic fertilizer application along with *Rhizobium* inoculation on selected soil properties, yield, and yield components of common bean and to determine the optimum combination of fertilizer management practices for each soil type.

2. Materials and methods

2.1. Description of the study area

A field experiment was conducted in 2021 and 2022 at Kokate, Hawassa, and Alage in Southern Ethiopia. The Kokate site is found at 390 km south of Addis Ababa and 5–15 km east of Wolaita Sodo in Wolaita zone, Southern Ethiopia. The Hawassa site is found in Hawassa University Main Campus at 273 km south of Addis Ababa in Sidama Region, Ethiopia. The Alage site is found at 217 km south of Addis Ababa and 38 km west of Bulbula town in the vicinity of Rift Valley Lakes (Abijata and Shaalla). The geographical features, and elevation of the studied sites were presented in Table 1.

2.2. Treatments and experimental design

Experimental design was arranged by factorial arrangement in a randomized complete block design (RCBD) with three replications at each site. Triple superphosphate (TSP) (46 % P_2O_5) was used as inorganic fertilizer, compost (C) and biochar (B) were used as organic fertilizer and *Rhizobium* inoculation (RI:HB 429) was used as biofertilizer. Three levels of inorganic fertilizer (0, 42.5, and 85 kg TSP ha^{-1} for KK; 0, 29, and 58 kg TSP ha^{-1} for HW, and 0, 35.5, and 71 kg TSP ha^{-1} for AL) and three level of organic fertilizer (0, 5 t B ha^{-1}, 5 t C ha^{-1}) and 500 g ha^{-1} of RI were used as treatments. Different levels of inorganic fertilizer were used for the different sites because the recommended rates of inorganic fertilizer varied among the sites, whereas the same levels of organic inputs and *Rhizobium* inoculation were applied for all sites.

2.3. Biochar production and compost preparation

Biochar was prepared from maize cob, a locally available feedstock, by a traditional earth-mound pyrolysis method in which the maize cob was burned in a pit with limited air at a temperature of about 300 °C for 2 h. Compost was prepared using crop residues (maize, wheat, barley, and millet), green leaves, farmyard manure, fresh and dry cow dung, and wood ash. A homogenized mixture of composting materials was composted in pits 2 m × 1.5 m wide by 1.5 m deep. All recommended management practices were employed until the materials were ready for use (matured compost). The chemical characteristics of the biochar and compost used in this presented in Table 2.

2.4. Treatment application and planting of the test crop

The experimental land was plowed three times by using an oxen-draw "local maresha." Triple superphosphate was applied in rows at planting, whereas the organic fertilizer (B and C) were applied and mixed with soil before 21 days of planting. A starter nitrogen at a rate of 18 kg N ha^{-1} was applied uniformly as urea (46 % N) to all plots during planting.

Rhizobium inoculum (RI; HB-429 strain) obtained from Menagesha Biotechnology PLC in Addis Ababa, Ethiopia. It was used to inoculate the common bean seed at a rate of 500 g inoculum per 15 kg seed, as recommended by the company. Inoculation of seeds was performed following the standard procedure modified by MoA [35]. Before planting two table spoons of sugar were dissolved in distilled water (300 ml) to form a sticker solution and the seed of a common bean were then mixed in sticker solutions until all seeds were evenly coated with the sticker. Finally, the seeds of the inoculated common bean were air dried for a few minutes and planted as per treatment.

The common bean variety “Hawassa Dume” was used as a test crop, which was released in 2008 by the Hawassa Agricultural Research Centre [36]. It is medium-sized with a dark red bean, a white flower, and a maturity period of 85–90 days. Moreover, it is high-yielding, widely grown, well adapted to the study areas, and highly preferred by farmers in the study areas. The seeds were sown at 10 cm and 40 cm between plants and rows, respectively. The experimental plots and blocks were separated by 0.5 and 1 m, respectively. The total experimental area was 342.2 m^2 (29.5 m * 11.6 m), and each experimental plot had an area of 6.4 m^2 (3.2 m × 2 m). Every plot consisted of a total of eight rows, six of which were subjected to data collection, and the remaining two rows, one from each side, were considered borders. It is worth noting that the plots used in the 2021 cropping year were changed in 2022 in order to avoid the residual effects of fertilizers.

2.5. Soil, biochar, and compost analyses

Soils of each site, B, and C used for these study were collected and drying, crushing, and sieving (<2 mm sieve) for laboratory analysis to investigate treatment effect. All soil, B, and C chemical compositions were determined after drying, crushing, and sieving (<2 mm sieve) for laboratory analysis. Three composite soil samples at a depth of 0–20 cm were collected by using an Edelman auger from each plot (0, TSP, B, C, BP, and CP), forming a total of eighteen composite soil samples from each site before and after harvesting. Collected soil samples were air dried and ground to pass through a 2-mm sieve for chemical analysis, whereas 0.5-mm sieve used for SOC and TN analysis. Soil pH was measured potentiometrically in a 1:2.5 (soil to water) ratio using a glass calomel combination electrode [37]. Soil organic carbon was determined by the wet digestion method [38]. Avail P was determined by the Olsen extraction method [39].

Table 1

Location and physiographic settings of the study sites.

Site	Soil pH	Geographic location		Altitude (m a.s.l)	MAR (mm)	MMaAT (°C)	MMiAT (°C)
		Latitude	Longitude				
KK	Strongly Acidic	6°52′42″	37°48′30″	2143	1300	29	14
HW	Neutral	7°3′3.2″	38°30′23″	1694	1100	33	12
AL	ModeratelyAlkaline	7°35′30″	38°24′59″	1585	693	34	17

*Note: MAR, Mean annual rainfall; MMaAT, Mean max annual temperature; MMiAT, Mean min annual temperature; KK, Kokate; HW, Hawassa; AL, Alage.

Table 2
Selected properties of the biochar and compost used in this study.

Experimental Materials	Ash Content (%)	pH (H_2O)	EC (dS m^1)	Avail-P (mg kg^{-1})	SOC	TN	CEC (cmol kg^{-1})
					(%)		
B	25.7	8.3	9.70	31.7	53.9	0.97	43
C	–	6.5	1.19	27.2	42.7	1.27	37

*Note: B, biochar; C, Compost; EC: electrical conductivity; Avail P: available phosphorus; TN: total nitrogen; CEC: cation exchange capacity.

2.6. Yield and yield components

The number of pods per plant (NPP) was determined at harvest by averaging the number of pods from five plants per plot. The number of seeds per pod (NSP) was recorded at harvest of five pods per plant and five plants per plot. The number of nodules (NN) was taken from the five common bean-uprooted plants, which were carefully washed in water to remove excess soil. The NN per plant was determined by counting all the nodules in each of the five plants and computing the average. Hundred seed weight (HSW) (g) was determined by weighing 100 randomly sampled seeds from the total harvest per plot, and the weight was adjusted to 10 % moisture level. Five sample plants per plot were collected and oven-dried at 72 °C for 48 h, and the weight was then converted to t ha^{-1} to estimate total above-ground biomass yield (BY). The grain yield (GY) (t ha^{-1}) was recorded from the six central rows and adjusted to 10 % moisture.

2.7. Economic analysis

The economic analysis was computed based on the procedure provided by CIMMYT [40]. Total variable costs were estimated by considering the current prices of TSP (38 Birr kg^{-1}), labor costs of B, and C preparation based on World Food Program work norms of 1100 Birr for 5 t ha^{-1}, respectively. Then, the total variable cost (TVC) was calculated as the sum of all costs that are variable or specific to a treatment against an unfertilized plot. The average yield was adjusted downward by 10 % to reflect the farmers' field yields, as described by CIMMYT [40]. The adjusted yield was multiplied by the market price to obtain the gross field benefit. The gross benefit was calculated by multiplying common bean grain by 30 Birr kg^{-1} (current prices). Net benefits (NB) were calculated by subtracting total costs from gross benefits for each treatment. Finally, a marginal rate of return (MRR) for the dominant treatments was estimated using the following formula:

$$MRR = \frac{(NB\ from\ superior\ dominant\ plot - NB\ from\ inferior\ dominant\ plot)}{TVC\ from\ superior\ dominat\ plot - TVC\ from\ inferior\ dominant\ plot} \times 100$$

2.8. Statistical analysis

The data recorded across sites and years were first checked for the assumption of homogeneity of variance to identify data requiring separate or combined analysis. Accordingly, Bartlett's test for homogeneity of variance for all parameters showed a significant difference, indicating their variances across sites are heterogeneous and suggesting separate analysis. The data for all parameters were similar between seasons; the interaction effect of inorganic, organic fertilizer and biofertilizer on common bean yield and yield components was combined because the variances among years were homogenous. Two-way analysis of variance (ANOVA) were

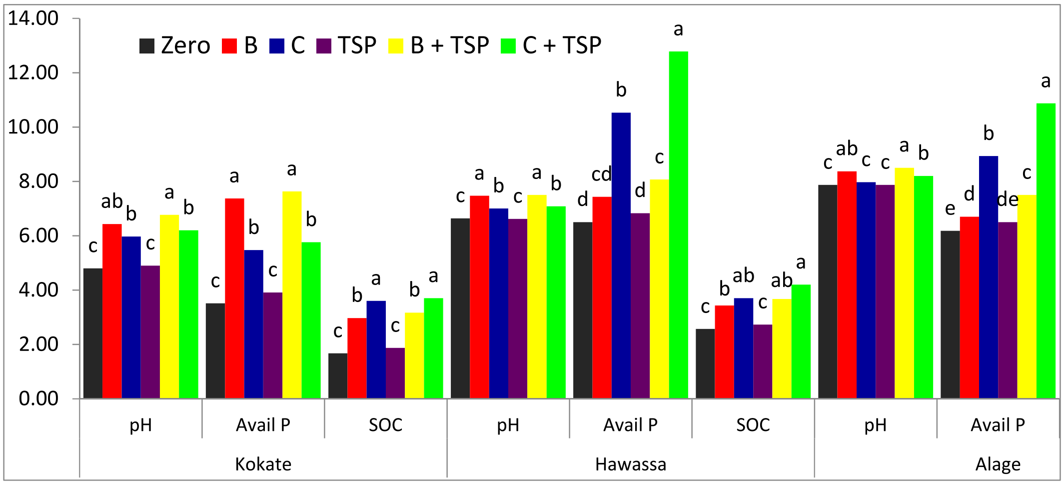

Fig. 1. Influence of amendments on selected physicochemical properties of the Kokate, Hawassa and Alage soils.

determined by using Statistical Analysis Software (SAS version 9.4) [41]. A mean comparison was performed using the least significant difference (LSD) test for the main effect significant parameters. Because this procedure has a high risk of committing a type I error rate when the number of treatments is large, Duncan's Multiple Range Test (DMRT) was used to compare differences between means for all the two-way interaction effect significant parameters.

3. Results and discussion

3.1. Effects of amendments on selected soil properties

The sole applications of biochar (B) and compost (C), as well as the combined treatments of B with TSP (BP) and C with TSP (CP), significantly improved ($p \leq 0.05$) soil pH, SOC, and avail P compared to the control and sole TSP treatments across the three soils studied (Fig. 1). The experimental soils were classified as very strongly acidic in KK, neutral in HW, and moderately alkaline in AL [42]. The increase in soil pH resulting from sole and integrated applications of organic fertilizers varied depending on the soil type. The most significant change in pH (1.2–1.9 units) occurred in the strongly acidic soils of KK, while the moderately alkaline soils of AL showed the smallest change (0.1–0.6 units). Likewise, Workineh et al. [43] reported that the addition of C and inorganic fertilizers increased soil pH. Obeng et al. [44] also found a change in soil pH from 5.1 to 6.1 due to the addition of B and manure. Similarly, Liu et al. [45] also showed that adding C and B can improve soil pH by up to 0.6 units. Consistent with our findings, higher pH changes were observed after B application compared with C [46]. This could be attributed to the high pH value of B and ash content compared with C in our experiment. Overall, B amendment can be used as a liming material because of its alkaline nature and high content of $CaCO_3$ [47].

The SOC contents were 1.7 %, 2.6 %, and 2.1 % for KK, HW, and AL, respectively, and were rated medium by Tadesse et al. [42]. The highest significant increase in SOC was obtained from the integrated CP application across all studied soils. The SOC values of the sole TSP application were not significantly different ($p \leq 0.05$) from the control treatment. The increased SOC due to sole and integrated applications of B, C, CP, and BP treatments compared with the sole TSP applied soils [48]. The results of increased SOC content and its influence on soil pH are also in agreement with previous findings [49–51]. The high SOC content of B and C in both the sole and integrated amendments BP and CP could highly contribute to SOC in the present study (Fig. 1). Increased SOC across various soil types promote soil microbial diversity and activity, thereby improving soil health. Similarly, B can provide carbon sources to stimulate soil microbial degradation of organic matter [27,52]. The C, N, and P sources from B are key factors in the increase of carbon and nutrient stocks in the soil [52,53].

The avail P content was rated as low in all studied experimental soils [39]. The low avail P content of the studied soils may be related to continuous cultivation and the P fixation nature of the soils [48]. This indicates that applying P containing inputs is necessary for improving crop yields and restoring the soil's avail P pool status. The results showed that avail P increased by 95 % in KK soil with the integrated BP amendment. In contrast, avail P levels increased by 68–88 % in HW and AL soils with the integrated CP amendment compared to the sole TSP application. This shows the variation in the effect of the amendments based on soil type. Thus, BP application was more efficient in increasing the avail P in the strongly acidic soils of KK, whereas CP was more efficient in the neutral soils of HW and moderately alkaline soils of AL. The higher increase in avail P with applications of integrated fertilizers compared with the control and sole inorganic TSP application may indicate that additional P could be released from C and B through the mineralization process and/or P in the ash, respectively [54,55]. The amendment of B resulted in decreased P sorption and

Table 3

Mean square values for yield and yield components of common beans analyzed at three sites.

Sources	DF	NPP	NSP	NN	HSW	GY	BY
Kokate							
Replication	2	13.58^{ns}	0.05^{ns}	76.44^{ns}	20.53^{ns}	0.07^{ns}	2.93^{ns}
TSP	2	107.79***	5.19***	12267.11***	11.69^{ns}	2.60***	17.25***
OF	3	6.92^{ns}	2.09**	1768.32***	41.22***	0.68***	42.43***
TSP[a]OF	6	7.54^{ns}	0.72^{ns}	304.19[a]	42.77***	0.05**	1.20**
Error	22	7.54	0.497	75.79	4.41	0.03	0.194
Hawassa							
Replication	2	18.04^{ns}	0.23^{ns}	16.44^{ns}	0.08^{ns}	0.19^{ns}	0.03^{ns}
TSP	2	210.38***	9.77***	15702.78***	3.00^{ns}	4.73***	23.34***
OF	3	74.06***	1.85***	7468.85***	0.77^{ns}	1.71***	9.28***
TSP[a]OF	6	10.46^{ns}	0.38^{ns}	1099.41***	5.74**	0.31**	1.25**
Error	22	6.19	0.25	137.23	1.36	0.06	0.17
Alage							
Replication	2	9.85^{ns}	0.09^{ns}	81.03^{ns}	18.86^{ns}	0.02^{ns}	0.01^{ns}
TSP	2	217.06***	1.78***	14650.11***	16.36^{ns}	4.28***	13.50***
OF	3	94.65***	0.39^{ns}	4748.56***	67.06***	1.83***	7.52***
TSP[a]OF	6	18.41^{ns}	0.18^{ns}	1016.56***	28.51**	0.21**	0.84**
Error	22	12.35	0.17	75.79	5.65	0.07	0.18

[a] Note: TSP, triple superphosphate fertilizer; OF, Organic fertilizers; NPP, Number of pods per plant; NSP, Number of seeds per pod; NN, Number of nodules; HSW, Hundred seed weight; GY, Grain yield; BY, Biomass yield; **, *** and ns refer to $p < 0.01$, 0.001, and not significant, respectively

increased avail P [56]. Pertinent to the present findings, the addition of vermicompost resulted in an increase of avail P by 37 % over the control in the calcareous soils of central Iran [57]. Overall, the increase in avail P due to the application of B, C, BP, and CP in the present study could be attributed to the release of P through various mechanisms, including the decomposition of OC in the soils and/or increasing P desorption [58]. Furthermore, organic amendments promote phosphatase activity by modulating soil aggregates [59]. When the soil pH is high, iron and aluminum species acquire hydroxyl groups and become less positive, limiting their interaction with P species and increasing the avail P. DeLuca et al. [60] found that B altered soil pH and CEC, altering P availability. Biochars anionic functional groups bind to metal oxides, allowing it to compete with phosphate ions for soil mineral adsorption sites, reducing phosphate adsorption [61–64]. Biochar influences and interacts with soil microorganisms by modifying the physicochemical qualities of soil and the number of P-dissolving bacteria, therefore impacting the soil's P cycle [65,66]. Biochar can significantly enhance soil microbial activity, enhancing P availability, C: N ratio, microbial diversity, and community structure compared to fertilizer treatment. Humic compounds, as an essential component of soil, have a critical role in increasing the number of phosphorus-solubilizing microorganisms [67]. Furthermore, the surface functional groups of humic substances can lower the number of P adsorption sites on the soil surface resulting from chelation, as well as the rate of calcium phosphate production [68]. Thus, the avail P contents in the soil increased from very low to moderate after the application of B, C, BP, and CP (Fig. 1).

3.2. *Effects of organic fertilizers and inorganic fertilizer on yield and yield components*

3.2.1. *Number of pods per plant (NPP) and number of seeds per pod (NSP)*

The interaction between TSP levels and organic fertilizers on the number of pods per plant (NPP) and number of seeds per pod (NSP) in common beans was not significant across all sites (Table 3). However, the main effect of TSP levels brought significant variation on mean NPP and NSP in all studied sites (Table 3). The lowest mean NPP and NSP were recorded from control, whereas the maximum values were from 85, 58, and 71 kg TSP ha^{-1} in KK, HW, and AL, respectively (Table 4). This was in close conformity with the findings of Rafat and Sharifi [69] and Alemayehu [70], indicating a general trend toward more seeds per pod when P rates rise. The increase in NPP and NSP with an increase in TSP levels may be attributed to the fact that P availability promotes biological processes including nodulation, nitrogen fixation, and nutrient uptake in soil and rhizosphere environments [71]. Thus, in this study, TSP application resulted in increased common bean pod and seed numbers, which is the most important yield contributing parameters. This increase could be due to the release of essential nutrients that promote high vegetative growth and the translocation of photosynthetic assimilates to sinks.

The application of organic fertilizers and RI had significant effects ($p \leq 0.001$) on the NPP and NSP in common beans across all studied sites, except for NPP at KK and NSP at AL (Table 3). The highest NPP and NSP were achieved with the application of 5 t ha^{-1} of C, followed by 500 g ha^{-1} of RI at both HW and AL sites (Table 4). In contrast, at the KK site, the maximum NSP was obtained from the sole application of 5 t ha^{-1} of biochar. However, in all cases, the unfertilized plots produced the lowest NPP and NSP values (Table 4). Similar results were obtained by Santosa et al. [72] and Dereje et al. [73], who reported the highest number of common bean pods with the application of C. The significant increase in NPP and NSP of common bean may be because of the application of organic fertilizer, which may be attributed to the increased availability of N, P, and S fertilizers and other nutrients, which are crucial for supplying energy for seed development and grain filling [74]. Other studies have also revealed that NPP and NSP increase in response to P and organic fertilizer application with common bean, which is in conformity with the findings of this study [75–77]. The poor performance of RI strains utilized in inducing nitrogen fixation with common beans may be due to their inability to adapt to the harsh abiotic conditions (strong acidity) at the KK site [78,79]. Similar effects of RI were also reported for the NSP [79]. However, this result agreed with [80] for the two sites HW and AL. Inoculation of faba bean with rhizobia increased NSP by 11.4 % and NPP from 7 to 13.1 % compared with the uninoculated plant.

3.2.2. *Effect of inorganic TSP and organic fertilizers on number of nodules (NN) and hundred seed weight (HSW)*

The interaction effect between TSP levels and organic fertilizer on the mean NN and HSW of common beans was highly significant ($p \leq 0.001$) at all sites (Table 3). Maximum values of NN and HSW from the use of integrated application of 58 and 71 kg TSP ha^{-1} with

Table 4

Table 4. The main effects of TSP levels and organic fertilizer treatments on yield component parameters of common beans at sites.

Treatments (kg ha^{-1})	NPP			NSP		
	KK	HW	AL	KK	HW	AL
No TSP (control)	8.48^{b}	16.14^{c}	12.67^{b}	3.28^{c}	4.16^{b}	3.82^{b}
50 % TSP	9.68^{b}	21.65^{b}	19.38^{a}	3.97^{b}	5.30^{a}	4.65^{a}
100 % TSP	14.17^{a}	24.36^{a}	20.55^{a}	4.59^{a}	5.45^{a}	4.92^{a}
No organic fertilizer (control)	9.70	17.38^{c}	13.29^{b}	3.30^{c}	4.30^{b}	4.38
5 t ha^{-1} B	11.80	19.89^{b}	16.722^{ab}	4.40^{a}	4.67^{b}	4.42
5 t ha^{-1} C	11.00	24.24^{a}	20.33^{a}	4.22^{ab}	5.29^{a}	4.79
500 g ha^{-1} RI	10.60	21.36^{b}	19.78^{ab}	3.87^{bc}	5.16^{a}	4.71
CV%	15.27	11.25	20.05	17.86	8.61	9.06

*Note: RI, *Rhizobium* inoculation; 50 % TSP, 50 % of the site recommended kg ha^{-1}; 100 % TSP, 100 % of the site recommended kg ha^{-1};Means within a column followed by the same letter (s) are not significantly different at $p \leq 0.001$.

C (5 t ha^{-1}) at both HW and AL sites (Table 5). The plots with the application of B (5 t ha^{-1}) alone resulted in the lowest NN and HSW at both sites. However, at KK site, the maximum mean values of NN and HSW were obtained from plots received combined application of 85 kg TSP ha^{-1} with B (5 t ha^{-1}). While plot received *Rhizobium* inoculum alone produced the lowest NN and HSW at this site. The present finding is consistent with Awene et al. [81], where the integrated application of TSP with C produced the highest NN and HSW. Similarly, other studies reported a greater NN for peanuts and lentils through integrated applications of different organic and inorganic fertilizers to the soils [82–84]. The increase in nodule production in plants could be due to the release of nutrients from added fertilizers and improved root development associated with nitrogen fixation in common beans [73]. Others, such as Zengeni et al. [85], reported that manure application enhances native rhizobia populations, which operate as a source of carbon and provide an environment favorable for bacterial growth. As a result, the increase in NN and HSW could be attributed to improved soil rhizobia conditions because of increased P and other micronutrient contents of the soil. The effects of nitrogen's capacity to fill grains through biological nitrogen fixation and the contribution of P fertilizer to seed filling might be linked to the findings of this study. The inoculated treatments had significantly higher nodule numbers per plant than the uninoculated treatments [83]. Similarly, studies have shown that RI considerably affects the nodule dry weight of soybean together with starter N and common bean at different experimental sites [86,87]. Fekadu et al. [88] showed that an integrated application of compost (4 t ha^{-1}) and P (15 kg ha^{-1}) resulted in the highest seed weight in faba beans. In addition, Zahida et al. [89] found that using NPK, FYM, VC, and biofertilizer together resulted in much greater HSW than using just one of these fertilizers alone. To support this finding, Morad et al. [90] found that seed inoculation with the proper RI and inorganic P (13 kg ha^{-1}) during the early growth stage induced root nodulation and increased HSW. The increase in HSW with increasing levels of TSP and organic fertilizer treatments could be due to adequate nutrient supply from organic and inorganic fertilizer sources throughout the growing period, improved microbial activity, and a stronger root system [81]. This in turn may have accelerated metabolic processes, resulting in improved photosynthesis and efficient photosynthetic translocation from the sink to the source, resulting in higher seed weight. In this study, the effects of the integrated treatments on the NN and HSW varied across different soils. The combined application of BP had a more pronounced effect on NN and HSW at the KK site compared to the HW and AL sites, likely due to differences in soil pH.

3.2.3. *Effect of inorganic TSP fertilizer and organic fertilizers on grain yield (GY) and biomass yield (BY)*

Similar to NN and HSW, the interaction between inorganic and organic fertilizers significantly influenced both grain yield (GY) and biomass yield (BY) ($p \leq 0.01$) (Table 3). The impact of these fertilizer treatments varied across different soils. At the HW and AL sites, the highest grain and biomass yields were obtained with the integrated application of 100 % TSP combined with 5 t ha^{-1} of C (Table 5). In contrast, at the KK site, the maximum grain and biomass yields were achieved with the integrated application of 100 % TSP combined with 5 t ha^{-1} of B. For instance, combining TSP (50 % recommended kg ha^{-1}) with B and C (5 t ha^{-1}) increased the mean GY of the common bean by 28 %, 26 %, and 33 % at KK, HW, and AL, respectively (Fig. 2 A) while the BY increased by 28 %, 20 %, and 12 % at KK, HW, and AL sites, respectively, over sole inorganic fertilizer plots (Fig. 2 B). Similarly, increasing TSP levels from 50 % to 100 % kg ha^{-1} with organic fertilizer increased the GY of the common bean by 18 %, 23 %, and 24 % and the BY by 15 %, 10 %, and 23 % at the KK, HW, and AL sites, respectively, over sole TSP treatment.

The integrated application of 100 % TSP with C resulted in the highest values of GY and BY under soils of HW and AL sites. However, the results showed maximum GY and BY with the integrated application of 85 kg ha^{-1} TSP with B under strongly acidic soil condition of the KK site. Thus, the integrated application of TSP with C or B provided the highest GY and BY compared with sole and control treatments depending on soil type. The integrated use of TSP with B and sole B in the neutral or moderately alkaline soils of HW and AL sites did not perform well, but it was superior or comparable to the integrated use of compost and sole compost in the strongly acidic soils of KK. This difference could be attributed to soil type and acid reaction variations at KK, HW, and AL. The results are similar to those of other studies where common beans and maize had higher GY values with the integrated application of compost and mineral fertilizers [23,43]. High common bean GY was reported when integrated mineral NPK and chicken manure were applied [91]. Other

Table 5
Interaction effects of TSP levels and organic fertilizer treatments on nodule number of common bean over sits.

Treatments		NN			HSW		
TSP rate	OF	KK	HW	AL	KK	HW	AL
0	0	31.67^{e}	35.00^{f}	33.67^{e}	27.67^{c}	35.00^{d}	27.67^{d}
0	5 t ha^{-1} B	56.33^{d}	37.00^{f}	35.00^{e}	35.00^{bc}	36.33^{bcd}	31.33^{cd}
0	5 t ha^{-1} C	45.00^{de}	98.00^{cd}	46.33^{de}	34.67^{bc}	36.67^{bcd}	34.67^{bc}
0	500 g ha^{-1} RI	35.33^{e}	55.33^{f}	55.67^{cd}	31.33^{c}	37.33^{bcd}	35.67^{b}
50 %	0	57.00^{d}	112.67^{c}	92.00^{c}	35.00^{bc}	36.33^{bcd}	37.33^{ab}
50 %	5 t ha^{-1} B	64.33^{cd}	86.33^{de}	63.67^{c}	37.67^{ab}	36.33^{bcd}	35.00^{bc}
50 %	5 t ha^{-1} C	60.33^{d}	135.67^{b}	126.67^{a}	37.33^{ab}	37.33^{bcd}	37.00^{ab}
50 %	500 g ha^{-1} RI	46.67^{de}	94.00^{cde}	97.00^{b}	35.67^{b}	35.33^{d}	38.33^{ab}
100 %	0	95.00^{b}	158.00^{a}	132.67^{a}	38.00^{ab}	38.00^{bc}	38.67^{ab}
100 %	5 t ha^{-1} B	119.00^{a}	75.67^{e}	69.00^{c}	40.33^{a}	35.67^{cd}	37.67^{ab}
100 %	5 t ha^{-1} C	98.00^{b}	166.67^{a}	135.75^{a}	38.67^{ab}	41.00^{a}	40.33^{a}
100 %	500 g ha^{-1} RI	81.67^{bc}	133.00^{b}	128.33^{a}	38.33^{ab}	38.67^{b}	38.00^{ab}
CV%		12.13	12.13	10.32	5.86	6.61	3.40

*Note: TSP, triple superphosphate fertilizer; OF, Organic fertilizers; B, biochar; C, compost; NN, Number of nodules; HSW, hundred seed weight; Means within a column followed by the same letter (s) are not significantly different at $p \leq 0.001$.

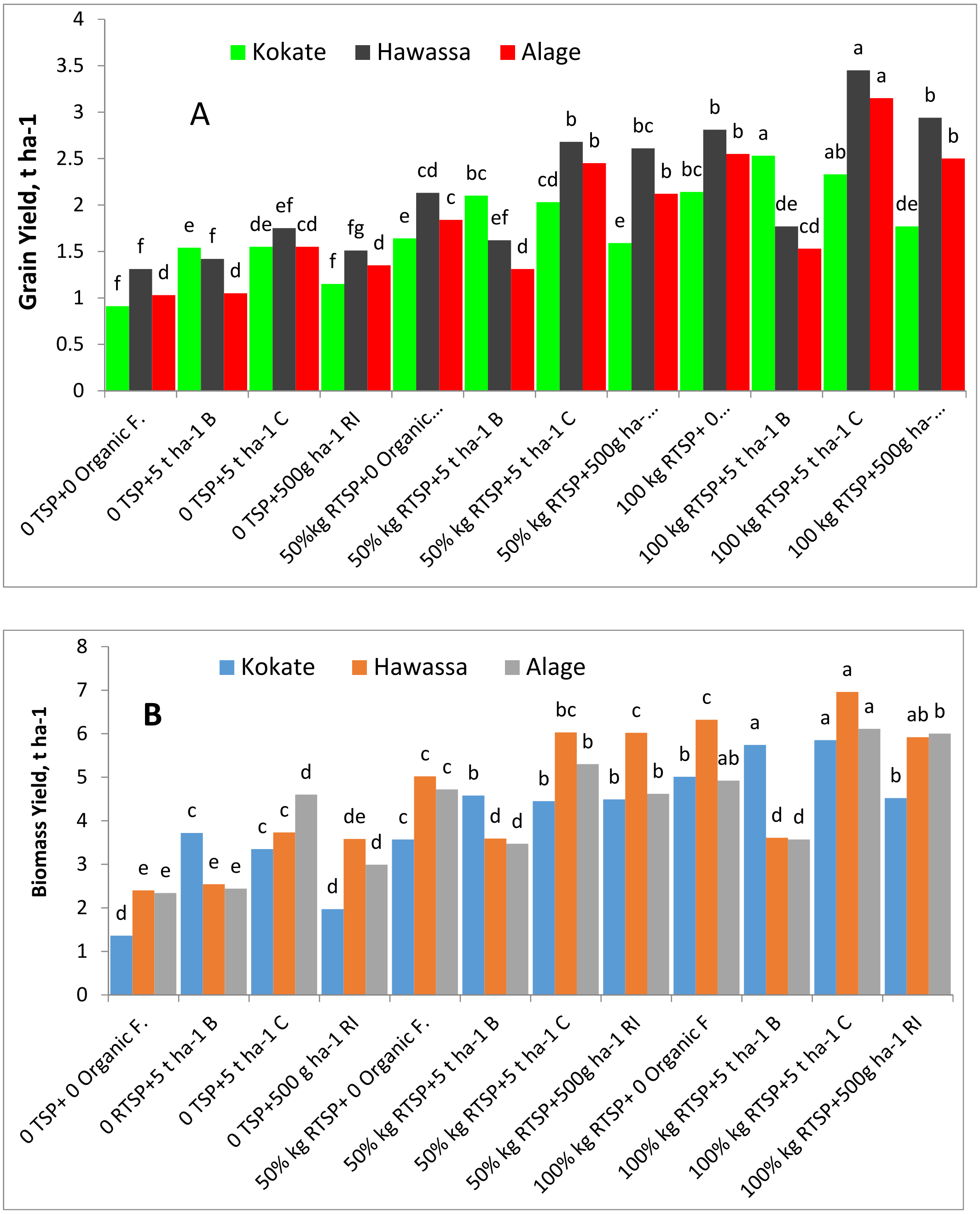

Fig. 2. Interaction effects of TSP levels and organic fertilizer treatments on Grain yield (A) and Biomass yield (B) of common beans over different sites.

studies have also found that the integrated application of organic and inorganic fertilizers resulted in higher yields and yield components compared with the sole application [92,93]. The maximum GY of common bean was also found for the integrated application of B and TSP [94,95]. The increase in GY of common bean under the integrated use of organic and inorganic fertilizers may be attributed to the fact that the supply of both sources in combination may promote soil quality, better root development, and nutrient use efficiency [23]. The other reason for the increased yield attributes could be the increased photosynthetic activity from the synergistic interaction between organic and inorganic fertilizers [96]. Assefa et al. [9] showed that inocula along with TSP increased the GY of chickpeas. This could indicate that the higher biomass growth with an increase in integrated fertilizer might be attributed to improved availability of essential plant nutrients and soil physical properties. Similar finding, organic fertilizers have a positive impact on plant growth by improving soil nutrient status and physical conditions [24]. According to Zhang et al. [63] found that the application of biochar can promote the growth of crop roots, increase crop yield, improve soil structure, and affect crop utilization efficiency of nutrients. Consistent with this, B can also improve soil nutrient availability by regulating soil microbial activities and metabolisms and then stimulate plant growth, change root structure, and increase photosynthesis [97,98], thereby improving plant nutrient uptake, biomass, and yield. The increase in BY due to integrated amendment (inorganic and organic fertilizer) was attributed to the increased leaf area index and number of branches per plant, which in turn improves light interception during photosynthesis and biomass accumulation [96]. Studies have shown a significant increase in the BY of legumes because of the application of integrated blended mineral NPSB fertilizer and C and integrated mineral NPK fertilizer and poultry manure [81,99,100]. For instance, Demissie et al. [100] showed that barley biomass increased by 11.5 t ha^{-1} after amending soils with a blended mineral NPSB fertilizer integrated with compost (C). Similar studies have also shown a significant increase in legume (common bean) BY due to the application of blended NPK fertilizer along with poultry manures or chicken manures [91,101]. Thus, the use of B stimulates plant growth and increases fertilizer use efficiency when integrated with inorganic fertilizer [102,103]. Furthermore, the enhanced P concentration in shoots and grains confirmed that the immediate positive effects of B on plant growth could be due to higher P availability [104].

3.3. Partial budget analysis

The partial budget analysis showed that the highest net benefits of 69,460 and 63,250-birr ha^{-1} was obtained from the integrated application of 29 and 35.5 kg TSP ha^{-1} with 5 t ha^{-1} C, respectively in HW and AL. This was followed by net benefits of 65,223 and 61,570-birr ha^{-1} from 58 to 71 kg TSP ha^{-1} with 5 t ha^{-1} C, respectively, in HW and AL. On the other hand, the lowest net benefits of 36,840 and 26,850-birr ha^{-1} were obtained from the addition of 5 t ha^{-1} B in HW and AL sites. However, the highest net benefit of 53,583-birr ha^{-1} was obtained from the integrated application of 85 kg TSP ha^{-1} with 5 t ha^{-1} B, followed by 85 kg TSP ha^{-1} and 5 t ha^{-1} C (51,545-birr ha^{-1}) in the KK site. On the other hand, the lowest net benefit (30,550-birr ha^{-1}) was obtained from the addition of RI at the KK site. The highest net benefit in response to the integrated application of organic and inorganic TSP fertilizers depended on the nature of the organic fertilizer and soil type. This was due to the differential effect of organic fertilizers on the soil type, which leads to varied effects on the increment of common bean grain yields.

4. Conclusions

The low soil fertility status of the study soils was influenced by the application of integrated biochar or compost and TSP fertilizer. These integrated applications significantly increased soil pH, SOC, and avail P as compared with the sole inorganic fertilizer application and control. Similarly, the integrated application also resulted in improved grain yield, biomass yield, and other yield component parameters compared with sole TSP fertilizer, sole organic fertilizers and the control treatment. The integrated application increased grain yield by 26%–33 % and 105%–138 % compared with sole inorganic TSP fertilizer and control treatment, respectively. The integrated use of biochar with TSP fertilizer and sole biochar in the neutral or moderately alkaline soils of Hawassa and Alage sites did not perform well, but it was superior or comparable to the integrated use of compost and sole compost in the strongly acidic soils of Kokate. This difference could be attributed to soil type and acid reaction variations at Kokate, Hawassa, and Alage. Moreover, the partial budget analysis showed that integrated nutrient management was economically feasible. The maximum net benefit was from integrated compost with TSP fertilizer applications at the Hawassa and Alage sites, whereas the maximum net benefit was from integrated biochar with TSP fertilizer at the Kokate site. Therefore, resource-poor farmers in southern Ethiopia can utilize biochar in acidic soils or compost in neutral or moderately alkaline soils by integrating with TSP fertilizer for improved yields and economic benefits of common bean. However, it is critical to assess the appropriate integration of different forms and levels of organic fertilizers with inorganic TSP and/or other fertilizers and the long-term effects and synergy in the soil types.

Data availability

There is no data deposited into a publicly available repository, hence it will be made available upon request.

CRediT authorship contribution statement

Rameto Wabela: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Girma Abera:** Writing – review & editing, Supervision, Methodology. **Bekele Lemma:** Writing – review & editing, Supervision, Methodology, Formal analysis. **Amsalu Gobena:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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