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Interactive effects of coffee husk biochar and NPSB rates on food barley (*Hordeum vulgare* L.) yield under limed and unlimed acidic soils

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Abstract
A field experiment was conducted in 2024 at Wacha Kebele, Chena District, southwestern Ethiopia, to evaluate the integrated effects of coffee husk biochar (CHB) and NPSB blended fertilizer on food barley under limed and unlimed acidic soil conditions. The treatments included three rates of NPSB fertilizer (50, 100, and 150 kg ha^{-1}) and coffee husk biochar (2.5, 5, and 7.5 t ha^{-1}), arranged in a randomized complete block design (RCBD). The combined application of CHB and NPSB significantly improved barley yield and profitability. The highest grain yield (4,150 kg ha^{-1}) was obtained from the combined application of 100 kg ha^{-1} NPSB and 5 t ha^{-1} coffee husk biochar (CHB) under limed conditions, whereas the highest net benefit (210,585.6 ETB ha^{-1}) and marginal rate of return (MRR; 5,785.33%) were also recorded with this treatment. Under unlimed conditions, the highest grain yield (3,119 kg ha^{-1}) was obtained from 100 kg ha^{-1} NPSB + 7.5 t ha^{-1} CHB, which also produced the highest net benefit (157,520.3 ETB ha^{-1}) and MRR (4,892.5%). These results indicate that the treatments maximizing grain yield coincided with the economically optimal treatments under both limed and unlimed conditions. Overall, the study demonstrates that integrating coffee husk biochar with NPSB fertilizer is an effective and economically viable strategy for improving food barley production in acidic soils. Based on agronomic and economic performance, the application of 100 kg ha^{-1} NPSB combined with 5 t ha^{-1} CHB under limed conditions is recommended for the study area and similar agroecologies. Further multi-location and multi-year studies are recommended to validate these findings and refine fertilizer recommendations.

Keywords Barley · Biochar · Lime · Net benefit · Soil acidity

Introduction

Food barley (*Hordeum vulgare* L.) is one of the world's most important cereal crops, ranking fourth after maize, wheat, and rice in terms of cultivated area and production[1]. Globally, it contributes approximately 7% of total cereal production and serves multiple purposes, including human consumption, livestock feed, and industrial processing[2]. Owing to its adaptability to diverse agroecological conditions, barley remains an essential component of food security and rural livelihoods in many developing countries, including Ethiopia[3]. In addition to its economic

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significance, barley is valued for its nutritional composition, providing complex carbohydrates, proteins, dietary fiber, vitamins, and essential minerals that support human health[4].

In Ethiopia, food barley is among the principal highland cereal crops and plays a critical role in household food security. However, despite its importance, barley productivity remains considerably below its genetic potential. In the Kaffa Zone of southwestern Ethiopia, average barley yield is estimated at 2.17 t ha^{-1}, which is lower than both the national average (2.45 t ha^{-1}) and the global average (2.96 t ha^{-1})[5]. This persistent yield gap is mainly attributed to declining soil fertility, continuous cultivation without adequate nutrient replenishment, soil acidity, imbalanced fertilizer application, and poor nutrient use efficiency[6]. The widespread reliance on blanket fertilizer recommendations that fail to account for site-specific soil conditions further exacerbates nutrient deficiencies and limits crop productivity[7].

Soil acidity is particularly severe in the humid highlands of southwestern Ethiopia, where intensive rainfall accelerates nutrient leaching and the accumulation of exchangeable aluminum[8]. Acidic soils reduce nutrient availability, restrict root development, and diminish crop growth and yield[9]. Although liming is commonly recommended to alleviate soil acidity, its effectiveness can be constrained by high costs, limited accessibility, and the continued depletion of soil organic matter. Consequently, there is growing interest in developing integrated soil fertility management strategies that simultaneously address soil acidity, nutrient deficiency, and declining soil quality through a combination of organic and inorganic nutrient sources[10].

Among organic amendments, biochar has emerged as a promising soil management technology due to its ability to improve soil physicochemical and biological properties[8]. Coffee husk biochar, produced through the pyrolysis of coffee-processing residues, is particularly relevant in coffee-growing regions such as Kaffa, where substantial quantities of coffee husks are generated annually. Application of coffee husk biochar can increase soil pH, improve cation exchange capacity, enhance nutrient retention, promote microbial activity, and improve soil water-holding capacity. Furthermore, biochar represents a sustainable approach to recycling agricultural wastes while contributing to long-term carbon sequestration and environmental conservation.

The use of blended fertilizers containing nitrogen (N), phosphorus (P), sulfur (S), and boron (B) has also gained attention as a means of addressing multiple nutrient deficiencies that frequently limit crop production in Ethiopian soils[11]. NPSB blended fertilizer provides a more balanced nutrient supply than conventional fertilizers and has been shown to improve crop growth, nutrient uptake, and yield. However, sole application of mineral fertilizers may not adequately restore soil health and can be associated with declining nutrient use efficiency under acidic soil conditions. Recent research increasingly emphasizes the integration of organic amendments with mineral fertilizers as a sustainable pathway for improving soil productivity and crop performance[12]. Studies conducted in different agroecological regions have demonstrated that combining biochar or other organic resources with inorganic fertilizers enhances nutrient availability, improves soil fertility, increases nutrient use efficiency, and promotes higher crop yields than the application of either source alone[13]. Integrated nutrient management practices have been reported to improve barley growth, yield components, grain yield, and soil physicochemical properties while supporting long-term agricultural sustainability[14].

Despite these encouraging findings, information remains scarce regarding the combined use of coffee husk biochar and NPSB blended fertilizer under limed and unlimed acidic soil conditions in southwestern Ethiopia[15]. Most previous studies have focused either on organic amendments or mineral fertilizers individually, with limited attention given to their interactive effects under varying soil acidity management practices. Moreover, no comprehensive study has evaluated the synergistic effects of coffee husk biochar, NPSB fertilizer rates, and liming status on food barley production in the acidic soils of Chena District, Kaffa Zone. Thus, this study introduces a novel integrated approach by simultaneously evaluating coffee husk biochar and NPSB blended fertilizer across limed and unlimed acidic soil conditions. The study aims to identify the most effective combination of organic and inorganic nutrient sources for enhancing the growth, yield, and yield components of food barley while improving soil fertility and resource-use efficiency. By utilizing locally available coffee-processing residues and balanced nutrient fertilization, the study seeks to develop sustainable and economically viable soil management practices tailored to the acidic soils of southwestern Ethiopia. The findings are expected to contribute valuable insights into climate-smart and circular agricultural systems, supporting improved food barley productivity and sustainable land management in the region.

Materials and methods

Description of the study Site

The field experiment was conducted during the 2024 cropping season at the Community Seed Bank Training Center in Wacha Kebele, Chena District, Kaffa Zone, Southwestern Ethiopia. The experimental site is geographically located at 7°12′30″ N latitude and 35°55′00″ E longitude, with an elevation of 2,118 m above sea level. Moreover, Fig. 1 clearly shows the map of the study site. Chena District is characterized by diverse agroecological conditions, comprising approximately 15% highland, 80% midland, and 5% lowland areas. The area experiences a humid sub-tropical climate with a bimodal rainfall pattern, consisting of the *Belg* (short rainy season) and *Meher* (main rainy season). The district receives an average annual rainfall of about 1,800 mm, while the mean minimum and maximum temperatures are 16 °C and 28 °C, respectively[16]. Similarly, climatic data were presented in Fig. 2. These climatic conditions are favorable for the production of a wide range of crops. Agriculture is the dominant livelihood activity in the area, with major crops including coffee, barley, enset, maize, sorghum, teff, wheat, faba bean, common bean, and potato. Coffee is the principal cash crop, while food barley is an important cereal crop cultivated for both household consumption and income generation. The soil of the experimental site

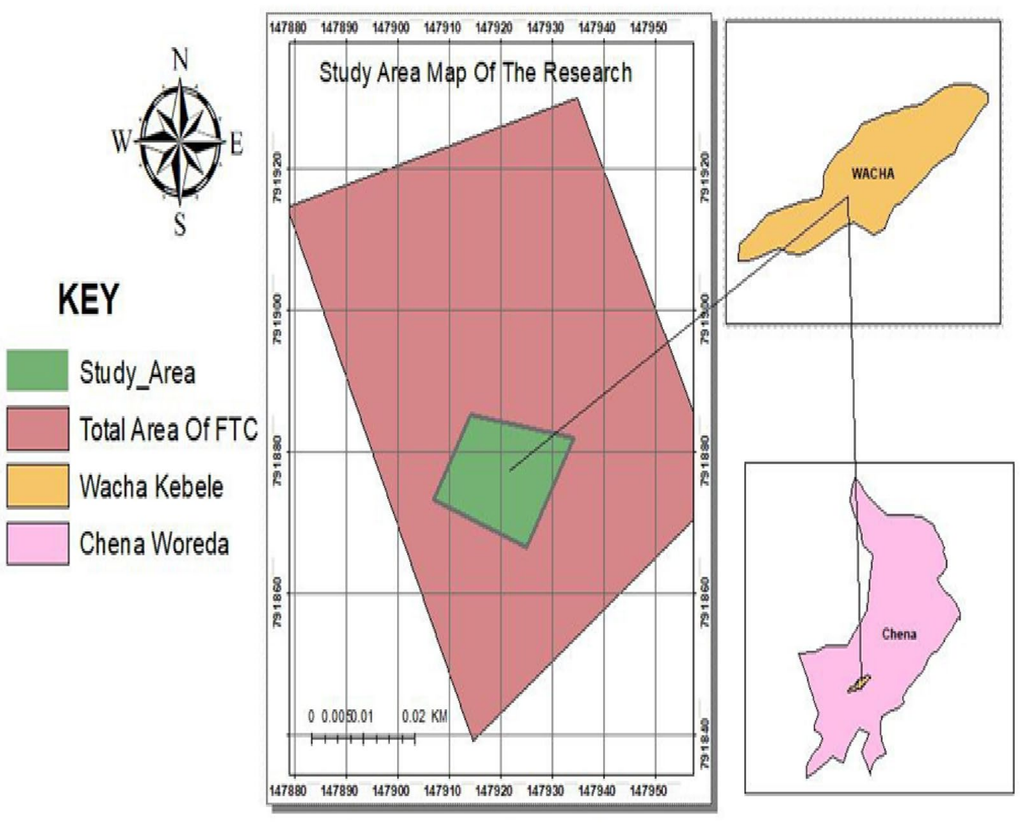

Fig. 1 Map of the study area.

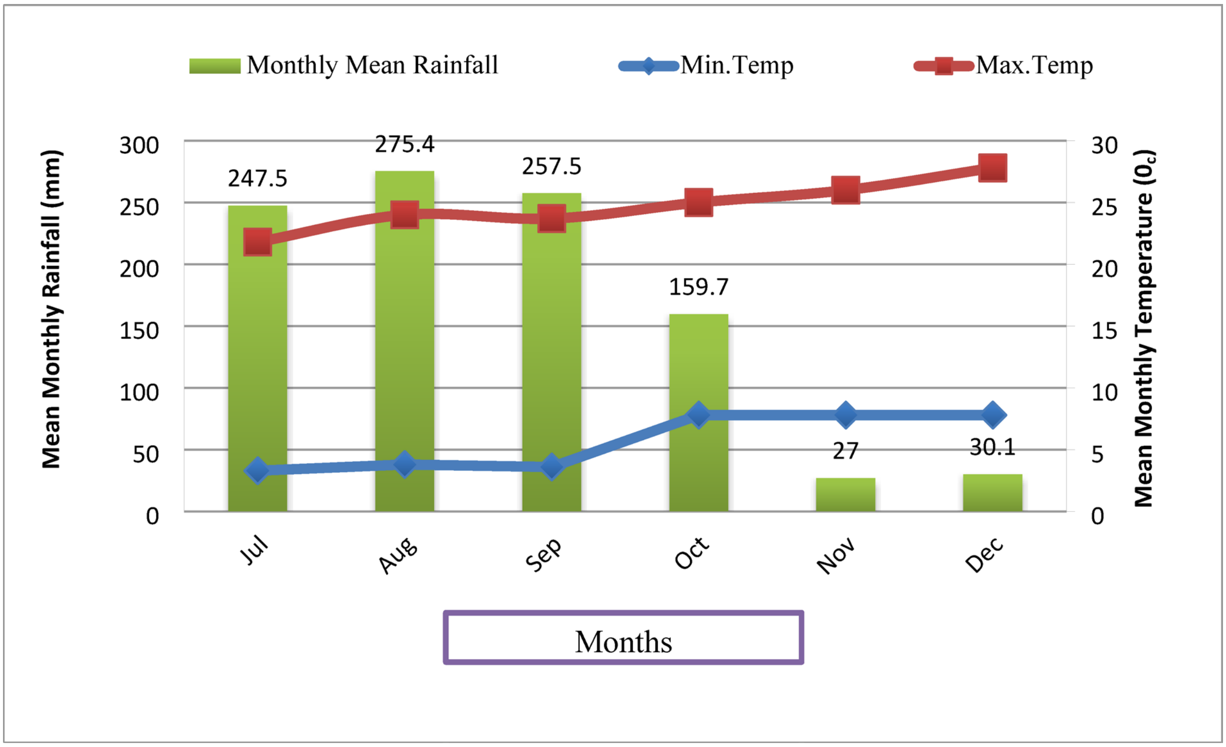

Fig. 2 Mean monthly temperature and mean rainfall data of the study site. Where: Tmin=Minimum temperature (o_c), Tmax = Maximum temperature (o_c).

is classified as clay loam, a texture that generally provides favorable conditions for crop production through its balanced water-holding capacity, nutrient retention, and aeration characteristics. Understanding the agroecological and soil conditions of the study area is essential for evaluating the effectiveness of soil fertility management practices and their impact on food barley productivity.

Experimental materials and inputs

The experimental materials used in this study included the food barley variety BH 1966, which was released by the Holetta Agricultural Research Center in 2017[17]. A blended NPSB (Nitrogen, Phosphorus, Sulfur, and Boron) fertilizer was applied, containing 18.9% nitrogen (N), 37.7% phosphorus pentoxide (P_2O_5), 6.95% sulfur (S), and 0.71% boron (B). Urea, with a nitrogen content of 46%, was also used as a supplementary nitrogen source. The organic amendment employed in the experiment was biochar, produced from coffee husk residues obtained from a dry coffee pulping station. Additionally, agricultural lime formulated based on soil test recommendations was incorporated into the study. This lime consisted of finely powdered calcium carbonate ($CaCO_3$) with a purity equivalent to 98% and was transported to the experimental site for application.

Treatments and experimental design

The experiment was conducted using a factorial treatment arrangement consisting of three rates of coffee husk biochar (CHB) (2.5, 5.0, and 7.5 t ha^{-1}) and three rates of NPSB blended fertilizer (50, 100, and 150 kg ha^{-1}). In addition to the factorial combinations, three control treatments were included as per the agricultural office recommendation for acidic soils of NPSB fertilizer alone (100 kg ha^{-1}), 5 t ha^{-1} of coffee husk biochar alone, and an absolute control receiving neither biochar nor NPSB fertilizer. All treatments were evaluated under two soil management conditions, namely limed and unlimed acidic soils. Consequently, a total of 12 treatment combinations were established. The experiment was laid out in a Randomized Complete Block Design (RCBD) with appropriate replications to minimize experimental error and account for field variability.

Experimental field management

The experimental field was prepared through three successive plowings using oxen, followed by manual leveling to ensure a uniform seedbed. The lime application rate was determined based on the soil-test recommendation using the exchangeable acidity method. Accordingly, agricultural lime was applied at a rate of 4 t ha^{-1} before planting. Then, lime and coffee husk biochar (CHB) were applied one month before planting. Lime was incorporated into all designated limed plots at a uniform rate based on soil test recommendations, whereas biochar was applied according to the respective treatment levels. Both amendments were thoroughly mixed into the top 20 cm of soil using a hand hoe to ensure uniform distribution and effective interaction with the soil.

Food barley was planted by hand in rows spaced 20 cm apart at a seed rate of 125 kg ha^{-1}. The blended NPSB fertilizer was applied as a basal fertilizer at sowing according to the assigned treatment rates. Since NPSB supplies a portion of the crop's nitrogen requirement, the amount of nitrogen contributed by each NPSB rate was accounted for when determining the supplemental urea rate. Accordingly, the urea rate for each treatment was calculated based on the difference between the recommended total nitrogen requirement of the crop and the nitrogen supplied by the respective NPSB treatment. This ensured that the target nitrogen rate was achieved through the combined application of NPSB and urea. All other agronomic practices, including weeding, hoeing, and pest management, were uniformly implemented across treatments following recommended barley production practices. At physiological maturity, the crop was harvested manually using hand sickles, sun-dried, and threshed separately for each plot to maintain treatment integrity. The field treatment combinations were presented in Table 1.

Data collected

Soil sampling and analysis

Before land preparation, a composite soil sample was collected from the experimental field to assess its physicochemical properties. Parameters analyzed included soil texture, pH, organic carbon content, total nitrogen (%), available phosphorus, available sulfur, available boron, and cation exchange capacity (CEC). Soil sampling was conducted to a depth of 0–20 cm using an auger, following a zigzag sampling pattern across five randomly selected points within the field. The collected subsamples were thoroughly mixed to form a composite sample, from which a 1 kg representative portion was taken as the working sample. Composite soil samples collected before planting were air-dried, gently crushed, and passed through a 2 mm sieve to facilitate the analysis of routine soil physicochemical properties. The 2 mm sieve is used for pH, EC, available P, available S, CEC,

Table 1 Treatment setup of the experiment.

Treatment	Coffee husk biochar (t ha^{-1})	NPSB fertilizer (kg ha^{-1})
Tr 1	Control	0
Tr 2	100% recommended CHB	0 recommended NPSB
Tr 3	0 coffee husk biochar	100% recommended NPSB
Tr 4	2.5	50
Tr 5	2.5	100
Tr 6	2.5	150
Tr 7	5	50
Tr 8	5	100
Tr 9	5	150
Tr 10	7.5	50
Tr 11	7.5	100
Tr 12	7.5	150

exchangeable cations, texture (after pretreatment), and many routine chemical analyses. For the analysis of soil organic carbon and total nitrogen, subsamples were further ground to obtain a finer particle size, as required by the respective analytical procedures, before laboratory analysis. The processed sample was then submitted to the Tepi Soil Analysis Laboratory for detailed physico-chemical analysis.

Soil texture was determined using the Bouyoucos hydrometer method[18]. Organic carbon content was assessed by the Walkley-Black method[19], while soil pH was measured in a soil-water suspension (1:2.5 ratio) using a pH meter. Total nitrogen was quantified using the Kjeldahl method[20]. Available phosphorus was measured using the Bray-II method[21], and cation exchange capacity (CEC) was determined through the ethanol (95%) extraction method[22]. Available sulfur was analyzed via the turbidimetric method[23]. Boron concentration was quantified by Atomic Absorption Spectrophotometry (AAS) following extraction with Diethylene Triamine Pentaacetic Acid (DTPA).

Biochar sampling and analysis

The coffee husk biochar (CHB) used in this study was prepared manually using locally available materials and traditional techniques, following these steps:

i. Fresh coffee husks of 250 kg were collected from nearby coffee processing sites.
ii. The husks were sun-dried for about one week until the moisture content dropped below 15%. A conical earth pit was then dug to serve as the pyrolysis chamber, with a small amount of firewood placed at the base to initiate combustion.
iii. The dried husks were gradually added to the pit, allowing the fire to spread slowly upward for up to 24 h with 450–500 °c to find a balance between biochar stability, alkalinity, nutrient retention, and CEC. The top of the pit was partially covered with clay or soil to limit oxygen and promote slow pyrolysis.
iv. The husks were stirred occasionally to ensure uniform carbonization. When the husks turned black and released white smoke, the fire was extinguished by sprinkling water to stop combustion.
v. After cooling, the biochar was crushed and sieved through a 2 mm mesh to achieve a uniform particle size suitable for soil application.
vi. The processed biochar was stored in dry sacks to prevent moisture absorption and maintain quality until use.

Then, the prepared biochar was characterized for several key properties, including pH, available organic carbon (OC), total nitrogen (TN), available phosphorus (P), available potassium (K^+), cation exchange capacity (CEC), and the carbon-to-nitrogen (C: N) ratio. The pH of the biochar was measured in distilled water at a 1:10 biochar-to-water mass ratio, following the procedure outlined by[24]. Organic carbon content was determined using the Walkley-Black method[19], while total nitrogen was quantified by the Kjeldahl method. Available phosphorus was measured using the Olsen method[25], and available potassium was analyzed using flame photometry. Cation exchange capacity (CEC) was estimated by titrimetric ammonium distillation, with displacement by sodium, following the procedure for soils with a pH of 7 using a 1 N ammonium acetate solution. Additionally, the ash content of the biochar was determined by the dry ash method, employing a high-temperature muffle furnace capable of maintaining temperatures between 500 and 600 °C.

Agronomic data collection

Crop phenology parameters *Days to heading (days)*: Were recorded by counting the number of days from sowing until 50% of the plants in each plot began to flower.

Days to physiological maturity (days): Were noted as the number of days from sowing to the date when approximately 90% of the peduncles in each plot turned to a yellow straw color, indicating maturity.

Growth parameters *Plant height (cm)*: It was measured in centimeters as the average distance from the soil surface to the tip of the spike, excluding the awn, at full maturity. Measurements were taken from ten randomly selected plants within each plot.

Spike length (cm): It was measured in centimeters as the distance from the base to the tip of the main spikes, excluding the awns. The average spike length for each plot was determined from measurements taken from ten randomly selected plants.

Yield and yield components *Effective tillers per plant (m^2):* Referring to spike-bearing tillers, were determined by averaging the count of fertile tillers from five randomly selected plants in each plot.

The number of seeds per spike ($Spike^{-1}$): Was determined by calculating the average number of seeds generated on each plant's primary tiller. This calculation was based on observations from ten randomly selected plants in each plot.

Above-ground biomass yield ($kg\ ha^{-1}$): It was determined by harvesting all plants from the net plot area at physiological maturity. The harvested biomass was dried until a constant weight was obtained and then weighed. The biomass yield was expressed on a dry matter basis.

Thousand-seed weight ($kg\ ha^{-1}$): Expressed in grams, was determined by weighing 1000 seeds randomly taken from each plot.

Grain yield ($kg\ ha^{-1}$): Measured in kilograms per hectare, was determined by measuring the grain obtained from each plot and adjusting its moisture content to 12.5%.

Harvest index (%): Was calculated as the ratio of dry grain yield to the above-ground biomass yield per plot, expressed as a percentage.

Data analysis

Separate analyses of variance (ANOVA) were performed for each management approach, and the results were subsequently combined across all approaches for each parameter. The analysis was carried out using the PROC GLM procedure, appropriate for randomized complete block designs, in SAS version 9.4[26]. Treatments that showed significant differences were further analyzed using the least significant difference (LSD) test for mean separation at a 5% significance level.

Results and discussion

Selected physico-chemical properties of soil

Soil texture analysis indicated that the experimental site is classified as clay loam, with a particle size distribution consisting of 18% sand, 42% clay, and 40% silt (Table 2). Soil texture is a key physical property that significantly influences nutrient availability, organic matter content, aeration, and water retention capacity[27]. According to[28], wheat and barley are most effectively grown in well-drained loam to clay loam soils, making the soil texture of the experimental site favorable for barley production. The soil analysis also revealed an organic carbon content of 18.9 mg kg^{-1}, which falls within the low range (Table 2). This suggests that organic carbon may be a limiting factor for crop growth at the experimental site.

The soil pH (measured in a 1:2.5 soil-to-water ratio) was found to be 5.4 (Table 2), classifying the soil as highly acidic according to the EthioSIS[29] classification system. Highly acidic soils are often unsuitable for most crops and typically require soil amendment practices to improve their condition. To mitigate the effects of acidity, the application of lime is commonly used by farmers to raise the pH and create a more conducive environment for barley cultivation.

Table 2 Soil physico-chemical properties before sowing.

Soil properties		Unit	Values	Rating	References
Particle size distribution	Sand	%	18		
	Silt	%	42		
	Clay	%	40		
Textural class		%	Clay loam		29
Organic carbon		mg kg^{-1}	18.9	Low	29
Soil pH: water ratio, 1:2.5			5.4	Highly acidic	29
Total nitrogen		mg kg^{-1}	1.1	Low	29
Av. P in P_2O_5 form		mg kg^{-1}	93.6	High	29
CEC meq 100 g soil		cmol kg^{-1}	266	Medium	29
BD		(g cm^{-3})	1.37	Medium	30
E A		cmol kg^{-1}	5.2	High	29
Sulfur		mg kg^{-1}	20.8	Very low	29
Boron		mg kg^{-1}	6.0	Medium	29

Coml=cent mole; pH= hydrogen ion concentration; OC= organic carbon; TN= total nitrogen; Av. p (ppm)= available Phosphorus parts per million; CEC=cation exchange capacity; BD= bulk density; EA=exchangeable acidity; and mg kg^{-1}= milligram per kilogram.

The analytical results indicated that the total nitrogen (N) content of the experimental soil was 1.1 mg kg^{-1}, which falls within the very low range based on the classification by[31] (Table 2). This suggests that nitrogen is a limiting nutrient for crop production in the study area. This was due to continuous cultivation, low organic matter content, and nutrient removal through crop harvest without adequate nutrient replenishment. Furthermore, the available phosphorus (P) content was found to be 93.6 mg kg^{-1} (Table 2), which is rated as high according to the EthioSIS[29] classification system. This discrepancy may be due to phosphorus fixation in acidic soils, which limits its bioavailability. Enhancing soil pH through liming can improve phosphorus availability and support optimal crop growth and productivity. Given that the critical phosphorus threshold for Ethiopian soils is approximately 15 mg kg^{-1}[29], phosphorus fertilization may be necessary to meet the nutritional demands of crops.

The cation exchange capacity (CEC) of the experimental soil was measured at 26.6 cmol (+) kg^{-1} (Table 2), which is considered medium according to the[29] rating. While this level of CEC indicates a moderate capacity to retain and exchange nutrients, it also implies that the soil has limited buffering capacity against chemical changes. CEC plays a vital role in nutrient retention, soil structure stability, pH buffering, and the effectiveness of fertilizer applications. Therefore, improving CEC through organic matter amendments and appropriate nutrient management is essential to enhance soil fertility and crop productivity.

The available sulfur content of the soil at the study site was measured at 20.9 mg kg^{-1} (Table 2), which falls within the very low range according to the[29] classification. This indicates a potential sulfur deficiency, suggesting the need for the application of sulfur-containing fertilizers. The low sulfur level may be attributed to the depletion of organic matter and the limited use of sulfur-based mineral fertilizers in the area. The available boron content was found to be 6 mg kg^{-1} (Table 2), which is categorized as medium based on[29] standards. This suggests a minimal risk of boron deficiency under current conditions.

In conclusion, the soil at the experimental site possesses favorable physical properties, such as a clay loam texture and moderate organic matter content. However, the high acidity level presents a major constraint to crop productivity, particularly for barley. The implementation of soil amelioration strategies, such as liming, is essential to improve soil pH and create conditions more suitable for barley cultivation. Although the soil exhibits moderate total nitrogen content, the availability of phosphorus is low, and the cation exchange capacity (CEC) is also classified as low. These nutrient limitations highlight the need for integrated soil fertility management practices, including pH correction and the application of appropriate mineral and organic fertilizers, to enhance nutrient availability and improve crop growth and yield performance.

Biochar sampling and analysis

Detailed chemical characteristics and disquisition results of coffee cocoon memoir housekeeper are presented in Table 3. The memoir housekeeper was extremely explosively alkaline with a pH- H2O of 8.03. The interchangeable

Table 3 Composition of Biochar used in the experiment.

Chemical properties of coffee husk biochar							
pH-H_2O (1:2.5)	CEC (Cmol (+) kg^{-1})	C (mg kg^{-1})	OM (mgkg^{-1})	C/N (%)	TN (mg kg^{-1})	Total P (mg kg^{-1})	Av.P (mg kg^{-1})
8.3	46	430.9	53.02	15.27	26	137.01	19.2

Where: CEC = cation exchange capacity, p= phosphorus, N= nitrogen, K= potassium, C: N=ratio of carbon to nitrogen, g kg^{-1} = gram per kilogram, Ppm = Parts per million, cmol kg^{-1}=Cent mole per kilogram.

Table 4 Combined effect of treatment on days to heading, and days to maturity under limed and unlimed conditions.

Treatment	Limed set of experiment		Unlimed set of experiment	
	DH (days)	DM (days)	DH (days)	DM (days)
Control	79.20^{g}	110.3^{i}	78.4^{j}	114.37i
5 t ha^{-1} CHB	82.43^{e}	114.7^{h}	80.273^{i}	117.38^{g}
100 kg ha^{-1} NPSB	81.10^{f}	120.4^{c}	82.133^{f}	116.87^{h}
2.5 t ha^{-1} CHB + 50 kg ha^{-1} NPSB	81.60^{f}	116.9^{g}	82.253^{e}	117.49 g
2.5 t ha^{-1} CHB+100kgha^{-1} NPSB	83.10c^{d}	117.3^{f}	83.577^{c}	117.38^{g}
2.5 t ha^{-1} CHB + 150 kg ha^{-1} NPSB	84.20^{b}	118.6^{e}	81.660^{g}	118.87^{f}
5 t ha^{-1} CHB + 50 kg ha^{-1} NPSB	82.53^{de}	119.8^{d}	80.773^{h}	117.35 g
5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB	86.83^{a}	121.6^{b}	85.523^{b}	121.06^{b}
5 t ha^{-1} CHB + 150 kg ha^{-1} NPSB	83.16^{c}	117.5^{f}	83.570^{c}	119.87e
7.5 t ha^{-1} CHB + 50 kg ha^{-1} NPSB	84.43^{b}	118.8^{e}	82.353^{d}	120.60^{c}
7.5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB	86.63^{a}	121.5^{a}	85.720^{a}	121.53a
7.5 t ha^{-1} CHB + 150 kg ha^{-1} NPSB	84.20^{b}	120.3^{c}	83.570^{c}	120.32^{d}
LSD (0.05)	0.57	0.08	0.56	0.26
Significance	**	**	**	**
CV (%)	8.41	8.57	0.04	2.27

Where: DF = days to Heading; DM= days to maturity; LSD= Least significance difference; and CV= Coefficient of variation; CHB= Coffee husk biochar; NPSB= Nitrogen Phosphorous Sulfur Boron; t ha^{-1}= Ton per hectare; kg ha^{-1} = kilogram per hectare; LSD= Least significance difference; NS = non-significant; **= highly significant; *= Significant. Mean values followed by the same letter in each treatment showed not significantly different at $p < 0.05$.

bases, interchangeable K^{+} (5.85 cmol (+) kg^{-1}), were all veritably high in content. This has led to the extremely high base saturation being noted. The soil test has extremely high CEC (46 cmol (+) kg^{-1}), TN (26 g kg^{-1}), and OC (430.9 g kg^{-1}). It's true that the alkalinity of memoir housekeeper is verified by different authors[32]. The C/N ratio was 15.27; nitrogen content occurs in organic matter naturally, and 19.2 g kg^{-1} of the accessible phosphorus (available P) out of the total phosphorus of 137.01 mg kg^{-1} was collected, and it had a low extractable P content (Table 3). Phosphorus retention in memoir housekeeper is a medium to give vital suggestions for the effective operation of P to boost crop product and sustain soil[33]. This might be caused by the memoir housekeeper's high alkalinity. This conclusion from a chemical examination of memoir housekeeper demonstrates that it has great eventuality for amending acidic soils.

Crop phenological and growth parameters

Days to heading (days)

Days to 50% heading were highly significantly ($P < 0.01$) affected by the combined application of coffee husk biochar (CHB) and NPSB fertilizer (Table 4). In general, the number of days required to reach 50% heading increased with increasing rates of CHB and NPSB fertilizer under both limed and unlimed conditions, indicating that improved nutrient availability prolonged the vegetative growth period before heading.

Under limed conditions, the maximum days to 50% heading (86.8 days) were recorded from the application of 5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB, whereas the control treatment reached heading in 79.2 days (Table 4). This represents a delay of 7.6 days, equivalent to a 9.6% increase over the control (Table 4). Similarly, under unlimed conditions, the highest value (85.72 days) was observed with 7.5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB, compared with 78.4 days in the control, representing a 9.3% increase (Table 4). Comparing the best treatments under the two management systems, limed plots headed 1.08 days later than unlimed plots, corresponding to a 1.3% increase. This suggests that liming further enhanced nutrient availability and vegetative growth, thereby slightly delaying reproductive development.

The delayed heading observed at higher CHB and NPSB application rates may be attributed to increased nitrogen availability, which promoted vigorous vegetative growth and prolonged the growth period before the onset of heading. In addition, improved soil conditions resulting from biochar and lime application likely enhanced nutrient uptake efficiency, contributing to the extended vegetative phase. These findings are consistent with previous studies. For example[34], reported that integrated application of inorganic and organic fertilizers delayed heading by stimulating vegetative growth. Similarly[13], found that fertilized plots generally headed later than unfertilized controls, while[35] demonstrated that NP fertilizer significantly influenced days to heading in barley. Overall, the results indicate that integrated application of CHB and NPSB fertilizer, particularly under limed conditions, delayed heading by approximately 9–10%, reflecting enhanced nutrient availability and improved crop growth.

Days to physiological maturity (days)

Days to 90% physiological maturity were highly significantly ($P < 0.01$) influenced by the combined application of coffee husk biochar (CHB) and NPSB fertilizer under both limed and unlimed conditions (Table 4). In general, the number of days required for barley to reach physiological maturity increased with increasing rates of CHB and NPSB fertilizer, indicating that integrated nutrient management prolonged the crop growth period.

Under limed conditions, the longest maturity period (121.6 days) was recorded from the application of 5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB, whereas the control treatment reached maturity in 110.3 days (Table 4). This represents an increase of 11.3 days, or approximately 10.2% over the control (Table 4). Likewise, under unlimed conditions, the highest maturity period (121.53 days) was obtained with 7.5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB, compared with 114.37 days in the control, representing a 6.3% increase (Table 4). A comparison of the best-performing treatments showed only a slight difference between limed and unlimed conditions, with maturity occurring approximately 1 day later under limed conditions (Table 4). However, the trend indicates that fertilizer-treated plots consistently required more time to mature than the unfertilized controls, regardless of management condition.

The delayed maturity observed with increasing CHB and NPSB rates may be attributed to enhanced nutrient availability, particularly nitrogen, which promotes vigorous vegetative growth and extends the growth period before senescence. Additionally, improved soil conditions resulting from biochar and lime application likely enhanced nutrient uptake and nutrient recycling, further prolonging crop development. These findings agree with previous reports by[13] and[35], who found that nitrogen application delayed crop maturity. Similarly[15] and 36, reported significant effects of integrated nutrient management on days to physiological maturity in barley, while[37], 38-39 observed delayed maturity with increased nitrogen fertilizer rates in wheat. Overall, the results indicate that integrated application of CHB and NPSB fertilizer increased days to physiological maturity by about 6–10% compared with the control, reflecting enhanced nutrient availability and prolonged crop growth.

Growth parameters

Plant height (cm)

Plant height was highly significantly ($P < 0.001$) affected by the combined application of coffee husk biochar (CHB) and NPSB fertilizer under both limed and unlimed conditions (Table 5). Generally, plant height increased

Table 5 Combined effect of NPSB and CHB fertilizers on plant height and spike length under limed and unlimed conditions.

Treatment	Limed set of experiment		Unlimed set of experiment	
	PH (cm)	SL (cm)	PH (cm)	SL (cm)
Control	8.363^{e}	92.4^{l}	8.25^{abc}	87.64^{e}
5 t ha^{-1} CHB	6.34^{g}	95.7^{i}	7.96^{c}	89.44^{de}
100 kg ha^{-1} NPSB	8.79^{cd}	97.6^{g}	8.42^{abc}	95.13^{ab}
2.5 t ha^{-1} CHB + 50 kg ha^{-1} NPSB	8.09^{f}	94.3^{k}	8.10^{bc}	89.94^{de}
2.5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB	8.36^{e}	99.2^{f}	8.28^{abc}	93.32^{bc}
2.5 t ha^{-1} CHB + 150 kg ha^{-1} NPSB	8.74^{d}	100.5^{d}	9.01^{a}	97.27^{ab}
5 t ha^{-1} CHB + 50 kg ha^{-1} NPSB	9.13^{b}	94.8^{j}	8.67^{abc}	88.5^{de}
5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB	9.53^{a}	102.5^{a}	8.77^{abc}	97.53^{ab}
5 t ha^{-1} CHB + 150 kg ha^{-1} NPSB	9.43^{a}	101.7^{c}	9.01^{a}	96.5^{ab}
7.5t ha^{-1} CHB + 50 kg ha^{-1} NPSB	8.96^{bcd}	97.2^{h}	8.66^{abc}	90.63^{cde}
7.5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB	8.09^{f}	100.4^{e}	9.03^{a}	97.68^{ab}
7.5 t ha^{-1} CHB + 150 kg ha^{-1} NPSB	9.00^{bc}	102.1^{b}	8.8^{ab}	99.04^{a}
LSD (0.05)	0.2407	0.0642	0.8518	5.1859
Significance	**	**	**	**
CV (%)	1.66	12.4	5.86	3.27

Where, PH= Plant height; SL= Spike length; CBC=Coffee husk biochar; NPSB=Nitrogen Phosphorous Sulfur Boron; t ha^{-1}= Ton per hectare; kg ha^{-1}= kilogram per hectare; LSD= Least significant difference; **: highly significant; *: Significant; and CV=Coefficient of variation. Mean values followed by the same letter in each treatment were not significantly different at $p < 0.05$.

with increasing rates of CHB and NPSB fertilizer, indicating that integrated nutrient management enhanced vegetative growth and crop development.

Under limed conditions, the tallest plants (9.53 cm) were obtained from the application of 5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB, while the control treatment produced the shortest plants (8.36 cm) (Table 5). This represents an increase of 1.17 cm, or approximately 14.0% over the control (Table 5). Similarly, under unlimed conditions, the maximum plant height (9.03 cm) was recorded with 7.5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB, compared with 8.25 cm in the control, representing a 9.5% increase (Table 5). Comparing the best-performing treatments, plant height under limed conditions was 0.50 cm greater than under unlimed conditions, corresponding to a 5.5% increase (Table 5). This indicates that liming improved the response of barley to CHB and NPSB fertilizer by reducing soil acidity and enhancing nutrient availability.

The increasing trend in plant height can be attributed to improved soil fertility, enhanced nutrient uptake, and reduced aluminum toxicity resulting from the combined application of CHB, NPSB fertilizer, and lime. Nitrogen supplied by NPSB likely stimulated vegetative growth, while CHB and lime improved soil conditions and nutrient use efficiency, promoting greater cell elongation and plant development. These findings are consistent with previous studies by[12,35,40–42], which reported significant increases in barley and wheat plant height following the integrated application of organic amendments, blended fertilizers, and lime. In general, the results demonstrate that integrated nutrient management significantly improved plant height, with the greatest response achieved when CHB and NPSB fertilizer were combined with lime.

Spike length (cm)

Spike length was highly significantly ($P < 0.01$) influenced by the combined application of coffee husk biochar (CHB) and NPSB fertilizer under both limed and unlimed conditions (Table 5). Generally, spike length showed an increasing trend with increasing rates of CHB and NPSB fertilizer, indicating the positive effect of integrated nutrient management on barley growth. Under limed conditions, the longest spike length (102.5 cm) was recorded from the application of 5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB, while the control treatment produced the shortest spikes (92.4 cm) (Table 5). This represents an increase of 10.1 cm, or approximately 10.9% over the control (Table 5). Similarly, under unlimed conditions, the maximum spike length (97.68 cm) was obtained with 7.5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB, compared with 87.64 cm in the control, corresponding to an 11.5% increase (Table 5).

Comparing the best-performing treatments under both management systems, spike length under limed conditions was 4.82 cm greater than under unlimed conditions, representing a 4.9% increase (Table 5). This indicates that liming enhanced the effectiveness of CHB and NPSB fertilizer by improving soil conditions and nutrient availability. The increase in spike length may be attributed to improved root growth, greater nutrient uptake, and enhanced phosphorus availability resulting from the combined application of biochar and NPSB fertilizer. Liming further reduced soil acidity and aluminum toxicity, creating favorable conditions for cell division and assimilate translocation, which promoted spike elongation.

These findings agree with those of[12,35,41,42], who reported significant improvements in barley spike length following the integrated application of organic and inorganic nutrient sources. Similarly[13], found that combining compost with inorganic NP fertilizer significantly increased spike length in wheat. Overall, the results demonstrate that integrated application of CHB, NPSB fertilizer, and lime effectively improved spike length, contributing to enhanced yield potential of food barley.

Yield and yield components

Number of productive tillers per plant (plant m^{-2})

The number of effective tillers was highly significantly ($P<0.01$) influenced by the combined application of coffee husk biochar (CHB) and NPSB blended fertilizer (Table 6). In general, the number of productive tillers increased progressively with increasing rates of CHB and NPSB under both limed and unlimed conditions, indicating a positive effect of integrated nutrient management on tiller formation. Under limed conditions, the highest number of effective tillers (438.58 tillers m^{-2}) was recorded from the application of 5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB, whereas the control treatment produced only 104.64 tillers m^{-2} (Table 6). This represents an increase of 319.1% over the control (Table 6). Similarly, under unlimed conditions, the maximum number of effective tillers (363.69 tillers m^{-2}) was obtained with 7.5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB, compared with 100.91 tillers m^{-2} in the control, corresponding to a 260.4% increase (Table 6).

Table 6 Effect of combination on productive tiller, seeds per spike, and thousand seed weight under limed and unlimed conditions.

Treatment	Limed set of experiment			Unlimed set of experiment		
	PT (plant m^{-2})	SPS (spike^{-1})	TSW (g)	PT (plant m^{-2})	SPS (spike^{-1})	TSW (g)
Control	104.64^{i}	32.21^{f}	38.54^{l}	100.91^{i}	29.753^{i}	36.47^{d}
5 t ha^{-1} CHB	142.34^{h}	35.08^{c}	42.65^{i}	248.78^{c}	27.767^{k}	41.15^{cd}
100 kg ha^{-1} NPSB	211.59^{e}	38.90^{a}	47.73^{d}	202.61^{f}	30.167^{f}	43.89^{abc}
2.5 t ha^{-1} CHB + 50 kg ha^{-1} NPSB	176.20^{g}	33.18^{e}	40.61^{k}	272.38^{b}	27.573^{l}	40.54^{cd}
2.5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB	220.8^{d}	36.00^{b}	41.43^{j}	247.50^{c}	30.067^{g}	42.82^{abc}
2.5 t ha^{-1} CHB + 150 kg ha^{-1} NPSB	186.97^{f}	38.71^{a}	49.34^{b}	138.75^{h}	32.567^{e}	44.65^{abc}
5 t ha^{-1} CHB + 50 kg ha^{-1} NPSB	180.81^{fg}	34.40^{d}	43.24^{h}	173.63^{g}	29.843^{h}	42.85^{abc}
5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB	438.58^{a}	42.11^{ab}	49.87^{a}	173.12^{g}	32.97^{d}	42.533^{bc}
5 t ha^{-1} CHB + 150 kg ha^{-1} NPSB	290.84^{b}	39.05^{a}	49.22^{c}	209.54^{e}	33.38^{b}	45.13^{abc}
7.5 t ha^{-1} CHB + 50 kg ha^{-1} NPSB	186.97^{c}	35.19^{c}	44.38^{g}	272.63^{b}	29.37^{j}	42.65^{bc}
7.5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB	286.23^{b}	39.00^{a}	44.66^{f}	363.69^{a}	33.633^{a}	46.31^{a}
7.5 t ha^{-1} CHB + 150 kg ha^{-1} NPSB	259.3^{c}	38.90^{a}	47.28^{e}	226.73^{d}	32.173^{c}	46.15^{ab}
LSD (0.05)	0.1094	0.5480	0.0288	0.032	0.0619	4.5975
Significance	**	**	**	**	**	**
CV (%)	2.16	1.51	4.23	0.68	0.18	6.26

Where: PT = Productive tiller; SPS: Seeds per spike; TSW= Thousand seed weight; LSD= Least significant difference; and CV = Coefficient of variation. CBC: Coffee husk biochar; NPSB: Nitrogen, Phosphorus, Sulfur, Boron; t ha^{-1}= Ton per hectare; kg ha^{-1}=kilogram per hectare; LSD = Least significant difference; ** highly significant; * =Significant; and CV= Coefficient of variation; Mean value followed by the same letter in each treatment showed not significantly different at $p<0.05$.

Comparing the highest values under the two management systems, liming increased the number of productive tillers from 363.69 to 438.58 tillers m^{-2}, an improvement of 20.6% (Table 6). This demonstrates the beneficial role of lime in enhancing nutrient availability and reducing soil acidity, thereby promoting tiller development. The increasing trend in effective tillers with higher CHB and NPSB rates may be attributed to improved phosphorus availability, enhanced nutrient uptake, and better root growth resulting from biochar and lime application. The integrated application of organic and inorganic nutrient sources likely created favorable soil conditions that stimulated cell division, vegetative growth, and tiller formation. Furthermore, readily available nutrients from NPSB fertilizer complemented the gradual nutrient release and soil-conditioning effects of CHB.

These results agree with previous findings by[43–45], and[46], who reported significant increases in productive tillers following integrated nutrient management and lime application. Similarly[13], found that the highest numbers of total and productive tillers were achieved at the maximum blended NPS fertilizer rate. Overall, the results indicate that the combined use of CHB, NPSB fertilizer, and lime significantly enhanced tiller production, which likely contributed to the higher grain and biomass yields observed in the study.

Number of seeds per spike (spike^{-1})

The number of seeds per spike was highly significantly ($P<0.01$) affected by the combined application of coffee husk biochar and NPSB fertilizer under both limed and unlimed conditions (Table 6). In general, the number of seeds per spike increased as CHB and NPSB application rates increased, indicating a positive response to integrated nutrient management.

Under limed conditions, the maximum number of seeds per spike (42.11 seeds spike^{-1}) was obtained from the application of 5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB, whereas the control treatment produced only 32.21 seeds spike^{-1} (Table 6). This represents an increase of 30.7% over the control (Table 6). Similarly, under unlimed conditions, the same treatment produced 33.63 seeds spike^{-1}, compared to 29.75 seeds spike^{-1} in the control (Table 6), representing a 13.0% increase. Comparing the best treatments under the two management systems, liming increased the number of seeds per spike from 33.63 to 42.11, corresponding to a 25.2% improvement (Table 6). This demonstrates that lime enhanced the effectiveness of CHB and NPSB fertilizer by reducing soil acidity and improving nutrient availability.

The higher number of seeds per spike in the integrated treatments can be attributed to improved availability of essential nutrients, particularly nitrogen and phosphorus, which promote spike development, floret fertility, and grain setting. In addition, CHB and lime likely improved soil conditions by reducing aluminum toxicity and enhancing nutrient uptake efficiency, resulting in better reproductive growth and increased kernel production.

These findings are consistent with previous studies. For example[47], reported significant increases in kernels per spike due to NPSB fertilizer application, while[48] found that integrating 5 t ha^{-1} FYM with 75% of the recommended NP fertilizer increased grain numbers per spike to 37 and 36.7. Similarly[42] and[13], reported that integrated use of organic and inorganic nutrient sources improved spike formation and grain number more effectively than either source applied alone. Overall, the results indicate that the combined application of 5 t ha^{-1} CHB and 100 kg ha^{-1} NPSB under limed conditions was the most effective treatment for maximizing the number of seeds per spike in food barley.

Thousand-seed weight (g)

The thousand-seed weight of food barley was highly significantly ($P<0.01$) affected by the combined application of coffee husk biochar and NPSB blended fertilizer (Table 6). A clear increasing trend was observed with increasing rates of CHB and NPSB fertilizer under both limed and unlimed conditions. The highest thousand seed weight under limed conditions (49.87 g) was recorded from the application of 5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB, whereas the maximum value under unlimed conditions (46.31 g) was obtained from 7.5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB (Table 6). In contrast, the lowest thousand seed weights were recorded in the untreated control plots.

Comparing the best-performing treatments, the thousand seed weight under limed conditions was 3.56 g higher than under unlimed conditions, representing a 7.7% increase (Table 6). This indicates that liming enhanced nutrient availability and uptake, resulting in heavier and better-filled grains. The progressive increase in seed weight with higher rates of CHB and NPSB further suggests a positive synergistic effect of organic and inorganic nutrient sources on grain development.

The improvement in thousand-seed weight can be attributed to enhanced phosphorus and nitrogen availability, which promote better grain filling, seed development, and overall crop performance. The limed treatments likely provided a more favorable soil environment by reducing soil acidity and improving nutrient use efficiency, thereby contributing to superior seed quality. These results agree with the findings of[7,12,43,49,50], who reported significant increases in thousand-grain weight following the integrated use of organic amendments and mineral fertilizers in barley. Similarly[41], found that integrated fertilizer management significantly improved thousand-seed weight, supporting the present study's findings. Overall, the results demonstrate that combining CHB and NPSB fertilizer, particularly under limed conditions, is an effective strategy for improving grain size and seed weight in food barley production.

Above-ground dry biomass yield (kg ha^{-1})

The above-ground dry biomass yield of food barley was highly significantly ($P<0.001$) affected by the interaction of coffee husk biochar and NPSB blended fertilizer (Table 7), indicating that biomass production responded strongly to integrated soil fertility management practices. Biomass yield generally increased with increasing rates of CHB and NPSB fertilizer under both limed and unlimed conditions, demonstrating the positive role of combining organic and inorganic soil amendments in enhancing barley growth.

Under limed conditions, the highest above-ground biomass yield (7,706.7 kg ha^{-1}) was obtained from the application of 7.5 t ha^{-1} CHB combined with 100 kg ha^{-1} NPSB fertilizer, whereas the control plots produced the lowest biomass yield (Table 7). Similarly, under unlimed conditions, the application of 7.5 t ha^{-1} CHB and 100 kg ha^{-1} NPSB resulted in the maximum biomass yield of 5,874.3 kg ha^{-1}, while the untreated control plots

Table 7 Combined effect of NPSB and CHB fertilizers on biomass yield, grain yield, and harvest index under limed and unlimed conditions.

Treatment	Limed set of experiment			Unlimed set of experiment		
	AGDBY (kg ha^{-1})	GY (kg ha^{-1})	HI (%)	AGDBY (kg ha^{-1})	GY (kg ha^{-1})	HI (%)
Control	2156.3^{g}	871^{l}	40.3^{bc}	1898^{k}	696.3^{l}	36.48^{j}
5 t ha^{-1} CHB	2932.0^{k}	1280^{k}	43.6^{abc}	2638.3^{j}	1104.7^{k}	41.80^{i}
100 kg ha^{-1} NPSB	3666.3^{h}	1710.7^{h}	46.4^{abc}	3264.7^{g}	1505^{h}	45.51^{g}
2.5 t ha^{-1} CHB + 50 kg ha^{-1} NPSB	3446.0^{j}	1356^{j}	39.3^{bc}	2757^{i}	1189^{j}	43.07^{h}
2.5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB	3830^{f}	1808^{g}	47.2^{abc}	3255^{g}	1627.7^{g}	51.5^{b}
2.5 t ha^{-1} CHB + 150 kg ha^{-1} NPSB	5124^{e}	2472^{f}	48.1^{abc}	4690.3^{e}	2204.7^{f}	46.90^{ef}
5 t ha^{-1} CHB + 50 kg ha^{-1} NPSB	3482.0^{i}	1573^{i}	45.2^{abc}	2959 ^{h}	1398.7^{i}	47.30^{e}
5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB	7379.3^{b}	4150.3^{a}	56.2^{a}	4446^{f}	2395.3^{e}	46.06^{fg}
5 t ha^{-1} CHB + 150 kg ha^{-1} NPSB	6026^{b}	3092^{d}	51.3^{a}	5709.3^{c}	2892.7^{c}	50.6^{ef}
7.5 t ha^{-1} CHB + 50 kg ha^{-1} NPSB	5789.3^{d}	2712^{e}	46.8^{a}	4996^{d}	2628^{d}	52.6^{b}
7.5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB	7706.7^{a}	4060.3^{b}	35.8^{c}	5874.3^{a}	3119^{b}	53^{d}
7.5 t ha^{-1} CHB + 150 kg ha^{-1} NPSB	7285.7^{c}	3920.3^{c}	50.8^{ab}	4996^{d}	2628^{d}	52.6^{b}
LSD (0.05)	1.6912	0.8802	12.89	28.83	1.239	0.8563
Significance	**	**	**	**	**	**
CV (%)	14.49	3.02	13.53	4.41	9.4	1.08

Where; AGDBY= Above Ground Dry Biomass yield; GY= Grain Yield; HI=Harvest index; NPSB= Nitrogen, Phosphorous, Sulfur, Boron; t ha^{-1}=ton per hectare; kg ha^{-1}=kilogram per hectare; ** =highly significant; * = Significant; LSD= Least significance difference; and CV= Coefficient of variation; CHB = Coffee husk biochar; Mean value followed by the same letter in each treatment showed not significantly different at $p<0.05$.

recorded the lowest values (Table 7). These results indicate a clear upward trend in biomass production as CHB and NPSB application rates increased, particularly when soil acidity was amended through liming.

A comparison between the two management systems reveals the substantial advantage of lime application. The highest biomass yield under limed conditions (7,706.7 kg ha^{-1}) exceeded the corresponding yield under unlimed conditions (5,874.3 kg ha^{-1}) by 1,832.4 kg ha^{-1}, representing a 31.2% increase (Table 7). This considerable improvement demonstrates the effectiveness of lime in creating favorable soil conditions that enhance the efficiency of nutrient utilization from both CHB and NPSB fertilizer. The higher biomass accumulation under limed conditions suggests that correcting soil acidity substantially improves plant growth and dry matter production. The positive response in biomass yield can be attributed to the ability of CHB to improve soil chemical properties and alleviate soil acidity. Coffee husk biochar likely increased soil pH and reduced the concentration of toxic aluminum (Al^{3+}) ions, thereby promoting root growth and enhancing nutrient absorption. Improved phosphorus availability resulting from higher soil pH may have stimulated root development and vegetative growth, leading to increased biomass production. The addition of NPSB fertilizer further supplied essential nutrients required for vigorous plant growth, while biochar improved nutrient retention and reduced nutrient losses. Consequently, the combined application of CHB and NPSB created a synergistic effect that supported greater biomass accumulation.

The trend observed in this study also indicates that biomass yield responded more strongly to integrated nutrient management when combined with lime than when applied alone. Although biomass production increased under unlimed conditions with the addition of CHB and NPSB, the magnitude of improvement was comparatively lower than under limed conditions. This finding highlights that nutrient additions alone may not fully overcome the constraints imposed by soil acidity. Instead, correcting acidity through lime application is essential for maximizing the benefits of both organic and inorganic nutrient sources. The increased biomass yield may also be associated with enhanced nutrient uptake and prolonged vegetative growth. Treatments receiving higher rates of CHB and NPSB fertilizer likely supported greater leaf area development, photosynthetic activity, and dry matter accumulation. Such improvements in vegetative growth ultimately contributed to higher above-ground biomass production. Since biomass yield is closely related to plant vigor and nutrient availability, the observed increases further confirm the effectiveness of integrated soil fertility management practices.

These results are in agreement with previous studies that reported significant increases in barley biomass yield following the application of blended fertilizers and organic amendments. For instance[42], observed improved biomass production in barley due to NPSB fertilizer application. Similarly, studies by[35] and[51] reported that liming materials and biochar amendments enhanced biomass yield through acidity amelioration and improved nutrient availability. Furthermore, the positive response recorded in the present study supports the findings of[13,35,52], who demonstrated that integrating organic and inorganic nutrient sources promotes better crop growth and dry matter production than the use of either source alone. In general, the findings demonstrate that above-ground biomass yield increased progressively with increasing CHB and NPSB fertilizer rates, with the greatest response achieved when these amendments were combined with lime. The highest biomass yield of 7,706.7 kg ha^{-1} obtained from 7.5 t ha^{-1} CHB and 100 kg ha^{-1} NPSB under limed conditions (Table 7) indicates that this integrated management strategy was the most effective in enhancing vegetative growth and biomass production of food barley. Therefore, the combined use of lime, coffee husk biochar, and NPSB fertilizer represents an effective approach for improving biomass yield and overall productivity of food barley grown on acidic soils.

Grain yield (kg ha^{-1})

The grain yield of food barley was significantly enhanced by the integrated application of coffee husk biochar and NPSB fertilizer, indicating a strong synergistic interaction among these soil amendments (Table 7). Under lime-managed conditions, the highest grain yield (4,150 kg ha^{-1}) was obtained from the application of 5 t ha^{-1} CHB combined with 100 kg ha^{-1} NPSB fertilizer, whereas the control treatment produced only 871 kg ha^{-1} (Table 7). This represents a 376.5% increase in grain yield over the control, demonstrating the substantial contribution of integrated nutrient management to barley productivity in acidic soils.

Similarly, under unlimed conditions, the maximum grain yield recorded was 3,119 kg ha^{-1} from the application of 7.5 t ha^{-1} CHB combined with 100 kg ha^{-1} NPSB fertilizer, while the control plots yielded only 696.3 kg ha^{-1} (Table 7). This corresponds to a 348.0% increase over the untreated control (Table 7). Although significant yield improvements were achieved without lime, the yields remained lower than those obtained under lime management, highlighting the importance of correcting soil acidity to maximize crop response to fertilizers and biochar. Besides, this higher barley yield observed in the biochar-treated plots compared with the control may be attributed to improvements in soil physical, chemical, and biological properties. Biochar likely enhanced soil moisture retention, nutrient availability, nutrient-use efficiency, and root growth, thereby promoting better crop performance even without direct nutrient addition. A comparison of the best-performing treatments under the two management systems further emphasizes the role of lime. The highest yield under lime management (4,150 kg ha^{-1}) exceeded the highest yield under unlimed conditions (3,119 kg ha^{-1}) by 1,031 kg ha^{-1}, equivalent to a 33.1% increase (Table 7). This substantial difference suggests that lime improved nutrient use efficiency and created a more favorable soil environment for barley growth. The enhanced performance can be attributed to the ability of lime to neutralize soil acidity, reduce exchangeable Al^{3+} toxicity, and increase the availability of essential nutrients such as phosphorus, calcium, and nitrogen.

The yield trend also indicated that increasing CHB and NPSB rates generally improved grain production compared with the control treatment. However, the magnitude of response was much greater when lime was included. This finding suggests that while CHB and NPSB fertilizer can supply nutrients and improve soil properties, their effectiveness is constrained in strongly acidic soils unless acidity-related limitations are first addressed through liming. Consequently, integrated management involving lime, biochar, and mineral fertilizer produced the most favorable outcomes. The significant increase in grain yield observed under integrated nutrient management was closely associated with improvements in yield-contributing agronomic traits such as plant height, spike length, and number of seeds per spike. Treatments that produced taller plants and larger spikes generally resulted in higher grain yields, indicating that enhanced vegetative growth translated into improved reproductive performance. Such responses are likely linked to better nutrient availability and improved soil conditions resulting from the combined application of CHB, NPSB fertilizer, and lime.

The present findings agree with previous studies reporting positive effects of integrating organic and inorganic nutrient sources on barley productivity. Several researchers[12,35,42,49,52] documented significant yield improvements following the combined application of organic amendments and mineral fertilizers. Likewise[41], reported that applying 50% vermicompost together with 50% recommended NP fertilizer produced a grain yield of 3,558.5 kg ha^{-1}, which was 446.9 kg ha^{-1} (14.4%) higher than the yield obtained from the full recommended NP fertilizer rate alone (3,111.6 kg ha^{-1}). This comparison demonstrates the synergistic benefit of integrating organic materials with inorganic fertilizers, similar to the positive interaction observed between CHB and NPSB fertilizer in the current study. Overall, the results clearly indicate that balanced soil fertility management involving CHB, NPSB fertilizer, and lime significantly enhanced food barley grain yield. The greatest yield gains were achieved when lime was combined with both organic and inorganic nutrient sources, emphasizing the critical role of soil acidity correction in improving nutrient availability and crop productivity. Therefore, the application of 5 t ha^{-1} CHB plus 100 kg ha^{-1} NPSB under lime management can be considered the most effective treatment for maximizing food barley grain yield under the acidic soil conditions of the study area.

Harvest index (%)

The harvest index of food barley was highly significantly ($P<0.001$) influenced by the combined application of coffee husk biochar (CHB) and NPSB blended fertilizer (Table 7). In general, harvest index increased with increasing rates of CHB and NPSB fertilizer under both limed and unlimed conditions, indicating improved efficiency in converting total biomass into economic yield.

The highest harvest index under limed conditions (56.2%) was obtained from the application of 5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB, while the highest value under unlimed conditions (53.0%) was achieved with 7.5 t

ha^{-1} CHB + 100 kg ha^{-1} NPSB (Table 7). This comparison shows that liming increased harvest index by 3.2% points, equivalent to a 6.0% improvement over the best unlimed treatment (Table 7). The increasing trend in harvest index suggests that integrated application of CHB and NPSB enhanced assimilate partitioning toward grain production rather than vegetative growth. Improved nutrient availability, particularly under limed conditions, likely promoted better grain filling and increased grain yield relative to total above-ground biomass. In addition, the reduction of soil acidity through liming may have improved nutrient uptake efficiency, further enhancing reproductive growth.

These findings agree with previous studies. For instance[12], reported significant improvements in barley harvest index following the combined application of NPSB fertilizer and organic amendments. Likewise[41], found that integrated application of NPSZnB and organic fertilizers significantly increased harvest index, while[13] and[51] demonstrated that liming acidic soils enhanced harvest index through improved nutrient utilization. In general, the results indicate that the integrated application of CHB, NPSB fertilizer, and lime improved harvest index, reflecting more efficient conversion of biomass into grain yield and contributing to higher productivity of food barley.

Partial budget analysis

The data analysis utilized a partial budget and marginal analysis to assess the economic viability of various treatment options. Partial budgeting enabled the comparison of costs and benefits associated with different treatments, while marginal analysis identified the optimal technology by contrasting costs and net benefits. The results indicated that the treatments receiving 5 t ha^{-1} CHB and 100 kg ha^{-1} NPSB blended fertilizer under limed conditions (Table 9), and 7.5 t ha^{-1} CHB and 100 kg ha^{-1} NPSB blended fertilizer under unlimed conditions (Table 11), yielded the highest net benefits per hectare. Conversely, the control plots yielded the lowest net benefits.

Despite the relatively high cost of NPSB blended fertilizer, the use of CHB in combination with NPSB blended fertilizer up to 100 kg ha^{-1} proved advantageous for smallholder farmers cultivating food barley. Additionally, the application of biochar was found to enhance the economic benefits of P_2O_5 fertilizer application. The marginal rate of return (MRR) analysis further supported these findings, with treatments involving the application of 5 t ha^{-1} CHB and 100 kg ha^{-1} NPSB blended fertilizer under limed conditions, and 7.5 t ha^{-1} CHB with 100 kg ha^{-1} NPSB blended fertilizer under unlimed conditions (Table 11), demonstrating MRR values above the acceptable minimum threshold of 100%. This suggests that for each unit of currency invested in food barley production using these treatments, the producer could expect to recover significantly more, indicating their economic feasibility. In general, the application of 5 t ha^{-1} CHB and 100 kg ha^{-1} NPSB blended fertilizer under limed conditions, and 7.5 t ha^{-1} CHB with 100 kg ha^{-1} NPSB blended fertilizer under unlimed conditions, was found to be economically viable, offering promising returns for smallholder farmers in these areas.

The partial budget analysis conducted under limed conditions identified five dominant treatments (T1, T3, T4, T7, T9, and T12) that outperformed others and were selected for further analysis of marginal rate of return (MRR) (Table 8). Among these treatments, Treatment 8(T8), which involved the application of 5 t ha^{-1} CHB with100 kg ha^{-1} NPSB fertilizer, yielded the highest net benefit at 210,585.6.2 ETB ha^{-1}, followed by Treatment 11(T11) with 201,319.1 ETB ha^{-1} (Table 8). However, when considering the marginal rate of return, Treatment 8(T8) also emerged as the most economically favourable option, recording an MRR of 5785.33% (Table 9). Treatment 6(T6) followed with a MRR of 4048.167%, and Treatment 11(T11) with 3814.96% (Table 9). These results indicate that for every Birr invested in Treatment 8 (T8), there was a return of 57.85 Birr, making it the most financially viable option among the selected treatments. Since all non-dominated treatments resulted in a rate of return above the minimum acceptable value (50–100%), Treatment 8 (T8) stands out as the best option in terms of its economic return. Therefore, it can be considered the most suitable treatment for maximizing economic benefits in agricultural practices under limed conditions.

In the partial budget analysis conducted under non-lime conditions, seven treatments (T1, T2, T3, T7, T10, T9, and T11) were identified as dominant, surpassing all other treatments (T4, T5, T6, T8, T10, T9, and T11)

Table 8 Partial budget analysis as influenced by blended NPSB fertilizer rate and CHB rate on acidic soil in food barley under limed conditions.

Treatment	Av. yield (Kg ha^{-1})	Adj. yield (kg ha^{-1})	TVC (Birr ha^{-1})	GFB (kg ha^{-1})	NB (kg ha^{-1})	Dominance
Control	871	783.9	587.925	47,034	46446.08	D
100 kg ha^{-1} NPSB	1710.7	1539.63	5354.72	92,377	87023.08	ND
2.5 t ha^{-1} CHB + 50 kg ha^{-1} NPSB	1356	1220.4	6765.3	73,224	66458.7	D
5 t ha^{-1} CHB	1280	1152	8364	69,120	60,756	D
2.5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB	1808	1627.2	9618.6	97,632	88013.4	ND
5 t ha^{-1} CHB + 50 kg ha^{-1} NPSB	1573	1415.7	10820.4	84,942	74121.6	D
2.5 t ha^{-1} CHB + 150 kg ha^{-1} NPSB	2472	2224.8	11990.7	133,488	121497.3	ND
5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB	4150.3	3735.27	13530.6	224,116	210585.6	ND
7.5 t ha^{-1} CHB + 50 kg ha^{-1} NPSB	2712	2440.8	14411.8	146,448	132036.2	D
5 t ha^{-1} CHB + 150 kg ha^{-1} NPSB	3092	2782.8	16601.5	166,968	150366.5	ND
7.5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB	4060.3	3654.27	17937.1	219,256	201319.1	ND
7.5 t ha^{-1} CHB + 150 kg ha^{-1} NPSB	3920.3	3528.27	20196.2	211,696	191,500	D

1$ is equivalent to 60 ETB; AV=Average yield; Adj.Y=Adjusted yield; TVC=Total variable cost; GFB= Gross field benefit; NB = Net benefit; Kg ha^{-1}=Kilogram per hectare; Birr ha^{-1}=Birr per hectare; ND = non-dominated; D=dominated; 1$ is equivalent to 60 ETB; Cost of NPSB fertilizers (44 ETB kg^{-1}); Cost of labor per person 100 Birr; Number of person participated during NPSB fertilizer application for 0 = 0; 50%= 4; for 100%=8 and for 150%=16; number of person participated during CHB application for 0 = 0; 50%= 3; for 100%= 6 and for 150%= 9; and the cost of harvesting was 0.75 birr kg^{-1}.

Table 9 Marginal rate analysis of return from blended NPSB fertilizer rate and CHB for food barely acidic soil under limed condition.

Treatment	TVC	NB	MC	MNB	MRR (%)
Control	587.925	46446.08	0	0	–
5 t ha^{-1} CHB	5354.72	87023.08	4766.795	40,577	851.24
2.5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB	9618.6	88013.4	4263.88	990.32	2172.59
2.5 t ha^{-1} CHB + 150 kg ha^{-1} NPSB	11990.7	121497.3	2372.1	33483.9	4048.16
5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB	13530.6	210585.6	1539.9	89088.3	5785.33
5 t ha^{-1} CHB + 150 kg ha^{-1} NPSB	16601.5	150366.5	3070.9	60219.1	837.11
7.5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB	17937.1	201319.1	1335.6	50952.6	3814.96

Where: T= treatment; TVC= total variable cost; NB = net benefit; MC= marginal cost; MNB= marginal net benefit; and MRR= marginal rate of return.

(Table 10). These dominant treatments were selected for further analysis of marginal rate of return (MRR). According to Table 10, the treatment with the highest net benefit was Treatment 11(T11), which involved the application of 100 kg ha^{-1} NPSB fertilizer with 7.5 t ha^{-1} CHB, yielding 157,520.3 ETB ha^{-1}. Treatment 12(T12) followed closely, with a net benefit of 148,694.2 ETB ha^{-1}, applying 150 kg ha^{-1} NPSB fertilizer with 7.5 t ha^{-1} CHB and 5 t ha^{-1} CHB.

However, when considering the marginal rate of return, Treatment 11(T11) emerged as the most economically favourable option, recording an MRR of 4892.5% (Table 11). Treatment 6(T6) followed with an MRR of 3352.8%, and Treatment 5 (T5) with 1548.9%. These results indicate that for every Birr invested in Treatment 11(T11), there was a return of 58.92 Birr, making it the most financially viable option among the selected treatments. Since all non-dominated treatments resulted in a rate of return above the minimum acceptable value (50–100%), Treatment 11(11) stands out as the best option in terms of its economic return. Therefore, it can be considered the most suitable treatment for maximizing economic benefits in agricultural practices under non-limed conditions.

Table 10 Partial budget analysis as influenced by blended NPSB fertilizer rate and CHB rate on acidic soil in food barley under unlimed conditions.

Treatment	Av. yield (kg ha^{-1})	Adj. yield (kg ha^{-1})	TVC (Birr ha^{-1})	GFB (Birr ha^{-1})	NB (Birr ha^{-1})	Dominance
Control	696.3	626.67	470.25	37600.2	37129.95	–
2.5 t ha^{-1} CHB + 50 kg ha^{-1} NPSB	1189	1070.1	5215.88	64,206	58990.12	ND
2.5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB	1627.7	1464.93	6652.58	87895.8	81243.22	ND
100 kg ha^{-1} NPSB	1505	1354.5	8245.67	81,270	73024.33	D
5 t ha^{-1} CHB + 50 kg ha^{-1} NPSB	1398.7	1258.83	9438.17	75529.8	66091.63	D
2.5 t ha^{-1} CHB + 150 kg ha^{-1} NPSB	2204.7	1984.23	10698.7	119053.8	108355.1	ND
5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB	2395.3	2155.77	12002.6	129346.2	117343.6	ND
7.5 t ha^{-1} CHB + 50 kg ha^{-1} NPSB	2628	2365.2	13316.8	141,912	128595.2	ND
5 t ha^{-1} CHB	1104.7	994.23	14294.1	59653.8	45359.7	D
5 t ha^{-1} CHB + 150 kg ha^{-1} NPSB	2892.7	2603.43	15905.3	156205.8	140300.5	ND
7.5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB	3232.3	2909.07	17023.9	174544.2	157520.3	ND
7.5 t ha^{-1} CHB + 150 kg ha^{-1} NPSB	3119	2807.1	19731.8	168,426	148694.2	D

1$ is equivalent to 60 ETB; D=Dominated; ND = Non dominated; AV=Average yield; AdY=Adjusted yield; TVC=Total variable cost; GFB=Gross field benefit; NB = Net benefit; Kg ha^{-1}=Kilogram per hectare; Birr ha^{-1}=Birr per hectare; Cost of NPSB fertilizers (44 ETB kg^{-1}); Cost of labor per person 100 Birr; Number of person participated during NPSB fertilizer application for 0 = 0; 50%= 2; for 100%= 4 and for 150%= 6; number of person participated during CHB application for 0 = 0; 50%= 2; for 100%=4 and for 150%= 6; and the cost of harvesting was 0.75 birr kg^{-1}.

Table 11 Marginal rate analysis of return from blended NPSB fertilizer rate and CHB for food barley acidic soil under unlimed condition.

Treatment	TVC	NB	MC	MNB	MRR (%)
Control	470.0025	37129.95	0	0	–
2.5 t ha^{-1} CHB + 50 kg ha^{-1} NPSB	5215.875	58990.12	4745.87	21860.2	460.6
2.5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB	6652.58	81243.22	1436.71	22253.1	1548.9
2.5 t ha^{-1} CHB + 150 kg ha^{-1} NPSB	10698.7	108355.1	4046.12	27111.9	3352.8
5 t ha^{-1} CHB + 100 kg ha^{-1} NPSB	12002.6	117343.6	1303.9	8988.5	689.3
7.5 t ha^{-1} CHB + 50 kg ha^{-1} NPSB	13316.8	128595.2	1314.2	11251.6	856.1
7.5 t ha^{-1}CHB + 100 kg ha^{-1} NPSB	15905.3	140300.5	2588.5	11705.3	4892.5
5 t ha^{-1} CHB + 150 kg ha^{-1} NPSB	17023.9	157520.3	1118.6	17219.8	1539.4

T= treatment; TVC= total variable cost; NB = net benefit; MC= marginal cost; MNB= marginal net benefit; and MRR= marginal rate of return.

Conclusion

The study demonstrated that the application of 100 kg ha^{-1} NPSB combined with 5 t ha^{-1} CHB under limed conditions produced the highest grain yield (4,150 kg ha^{-1}) and economic return (210,585.6 ETB ha^{-1}). Under unlimed conditions, 100 kg ha^{-1} NPSB combined with 7.5 t ha^{-1} CHB resulted in the highest grain yield (3,119 kg ha^{-1}) and net benefit (157,520.3 ETB ha^{-1}). These findings indicate that biochar can partially alleviate the adverse effects of soil acidity, while its integration with balanced mineral fertilization and lime provides a more effective strategy for maximizing crop performance. Therefore, the application of 100 kg ha^{-1} NPSB with 5 t ha^{-1} CHB under limed conditions is recommended for food barley production in acidic soils of the study area and similar agroecological zones. Where liming is not feasible, the combination of 100 kg ha^{-1} NPSB and 7.5 t ha^{-1} CHB may serve as a viable alternative. However, since this study was conducted at a single location and during a single cropping season, further multi-location and multi-season experiments are required to validate the findings under diverse agroecological conditions and to develop more robust recommendations for sustainable food barley production on acidic soils. In addition, future research should incorporate post-harvest soil characterization and nutrient use efficiency assessments to better understand the residual and long-term effects of coffee husk biochar on soil fertility, nutrient dynamics, and the sustainability of crop production systems.

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Data availability The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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