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Integrated vermicompost and blended NPSB fertilizer enhances soil physicochemical properties and barley (*Hordeum vulgare* L.) productivity in the acidic highlands of Western Ethiopia

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Abstract

Soil fertility depletion and acidity are major constraints to barley (*Hordeum vulgare* L.) production in the Ethiopian highlands. Integrated soil fertility management (ISFM) offers a sustainable solution, but site-specific recommendations are lacking for the Horro District. This study evaluated the integrated effects of vermicompost (VC) and blended NPSB fertilizer on soil physicochemical properties and barley yield. A factorial experiment was conducted during the 2023/2024 main cropping season using a Randomized Complete Block Design with three replications. Treatments comprised four VC rates (0, 1.25, 2.5, and 3.75 t ha^{-1}) and four NPSB rates (0, 50, 100, and 150 kg ha^{-1}). Soil samples were analyzed before planting and after harvest for pH, organic carbon (OC), total nitrogen (TN), available phosphorus (Av. P), sulfur (Av. S), boron (Av. B), cation exchange capacity (CEC), bulk density (BD), and texture. Barley yield and yield components were recorded, and partial budget analysis was performed. The initial soil was strongly acidic (pH 5.24) with low OC (1.23%) and very low Av. P (6.39 ppm). Integrated VC and NPSB application significantly ($p < 0.05$) improved all soil properties compared to the control. The combination of 3.75 t ha^{-1} VC with 100 kg ha^{-1} NPSB produced the highest OC (1.53%), TN (0.25%), Av. P (10.30 ppm), CEC (33.31 cmol(+) kg^{-1}), and grain yield (5.78 t ha^{-1}), while reducing BD to 1.25 g cm^{-3}. This treatment also yielded the highest net benefit (218,335.5 ETB ha^{-1}) with a marginal rate of return of 681.75%. We conclude that integrated application of 3.75 t ha^{-1} VC and 100 kg ha^{-1} NPSB is a sustainable, economically viable strategy to restore soil fertility and enhance barley productivity in the acidic Nitisols of Western Ethiopia. Long-term studies are recommended to evaluate residual effects across multiple cropping seasons.

Keywords: Barley, Blended Fertilizer, Integrated Soil Fertility Management, Soil Acidity, Vermicompost.

1. Introduction

Soil fertility decline is a primary impediment to agricultural productivity and food security in sub-Saharan Africa, particularly in the Ethiopian highlands [1, 2]. Intensive cultivation, continuous cropping, and the removal of crop residues, combined with low and imbalanced fertilizer application, have led to severe depletion of soil organic matter and essential nutrients [3, 4]. In Ethiopia, the national average nutrient depletion rates are alarmingly high, estimated at 122 kg N ha^{-1} yr^{-1} and 13 kg P ha^{-1} yr^{-1} [5]. This degradation is exacerbated by widespread soil acidity, which affects approximately 43% of the country's arable land, further limiting nutrient availability [6].

Barley (*Hordeum vulgare* L.) is a staple food security crop in the Ethiopian highlands, particularly for smallholder farmers [7]. However, national average yields (2.5 t ha^{-1}) remain far below experimental potential (>5 t ha^{-1}) [8]. This yield gap is primarily due to poor soil fertility deficiencies in nitrogen (N), phosphorus (P), sulfur (S), and boron (B) exacerbated by soil acidity [9, 10].

Historically, Ethiopian agriculture has relied primarily on urea and diammonium phosphate (DAP) as mineral fertilizer sources, which supply only N and P [11]. Since the 1970s, blanket recommendations of 64 kg N ha^{-1} and 20 kg P ha^{-1} have formed the basis of the national fertilizer strategy, irrespective of crop and soil type [20]. While N and P remain the most yield-limiting nutrients for major cereals such as teff, wheat, and maize in Ethiopia [6, 9], long-term application of N and P only fertilizers without complementary organic amendments has coincided with declining levels of other essential nutrients, including S and B, in many regions [12, 20]. Soil surveys have persistently revealed deficiencies of S, Zn, and B across large areas of the country [10, 14, 20], and national nutrient balance assessments indicate alarming depletion rates of both macro- and micronutrients [8]. To address these multi-nutrient deficiencies, the Ethiopian Ministry of Agriculture introduced blended NPSB fertilizer (18.9% N, 37.7% P_2O_5, 6.95% S, 0.1% B) in 2014–2016, establishing blending facilities to produce tailored blends for different soil types [13]. However, recent large-scale evaluations have found that while NPS adoption increased, there is no evidence that the blended fertilizers significantly improved crop yields, gross revenue, or household consumption compared to NP alone [13, 22]. Consequently, the government has revised its fertilizer strategy, with the 2026–2035 Fertilizer and Soil Health Roadmap now prioritizing N and P while recommending that other nutrients be supplied only when specifically required based on site-specific soil testing [6, 19]. This policy shift underscores the need for integrated approaches that combine appropriate mineral fertilizers with organic amendments such as vermicompost to address the full range of soil fertility constraints in a sustainable manner.

Nevertheless, the sole reliance on mineral fertilizers is not a sustainable solution. Their high cost, limited availability for smallholder farmers, and potential to exacerbate soil acidification and degrade soil physical properties necessitate integrated approaches [15, 16]. Organic amendments, such as vermicompost, offer a viable alternative.

Vermicompost, produced through the breakdown of organic materials by earthworms, is rich in humic substances, macro- and micronutrients, and beneficial microorganisms [17]. Its application improves soil structure, increases water-holding capacity, enhances cation exchange capacity (CEC), and supplies a slow-release source of nutrients, thereby mitigating soil acidity and improving overall soil health [18, 19].

Integrated Soil Fertility Management (ISFM) the synergistic combination of organic and inorganic fertilizers enhances nutrient use efficiency, sustains soil productivity, and increases crop yields [20, 21]. In Ethiopia, combining organic amendments (compost or vermicompost) with mineral fertilizers improves soil properties and boosts yields more than sole applications [22-24]. However, site-specific recommendations are essential given variability in soil types, agro-ecology, and farming systems.

The Horro District in Western Ethiopia is characterized by Dystric Nitisols, which are inherently acidic and prone to nutrient leaching [25]. Local farmers primarily use suboptimal rates of DAP and urea, with limited adoption of organic fertilizers, leading to persistent soil fertility depletion and low barley yields [26]. While blended NPSB and vermicompost have been studied elsewhere in Ethiopia [27, 28], no empirical evidence exists for their combined effects on soil properties and barley productivity in the Horro District. Therefore, this study evaluated the integrated effects of VC and NPSB on soil physicochemical properties, barley yield and yield components, and determined the most economically feasible treatment combination for local smallholder farmers.

Therefore, this study was conducted to evaluate the integrated effects of vermicompost and NPSB fertilizer on selected soil physicochemical properties and the yield and yield components of barley, and to determine the most economically feasible treatment combination for smallholder farmers in the Horro District. Specifically, we tested three overarching hypotheses (detailed in Section 2.7) that combined VC and NPSB application would: (i) improve soil properties compared to sole applications; (ii) enhance barley yield components and grain yield; and (iii) be economically viable for smallholder farmers.

2. Materials and Methods

2.1. Study Area Description

The field experiment was conducted during the 2023/2024 main cropping season at the Wallaga University Shambu Campus research farm in the Horro District, Horro Guduru Wollega Zone, Oromia Regional State, Ethiopia. The site is located between 9°34′30″ N and 9°37′42″ N latitude and 37°02′30″ E and 37°07′00″ E longitude, at an altitude of approximately 2,450 meters above sea level (Fig 1). The district has a subtropical climate with a unimodal rainfall pattern. The mean annual rainfall ranges from 800 to 2,200 mm, with the main rainy season occurring from June to September. The mean annual temperature ranges from 12.4°C to 24.6°C (Fig 2). The dominant soil type is Dystric Nitisols, characterized by moderate fertility but high inherent acidity [25, 29].

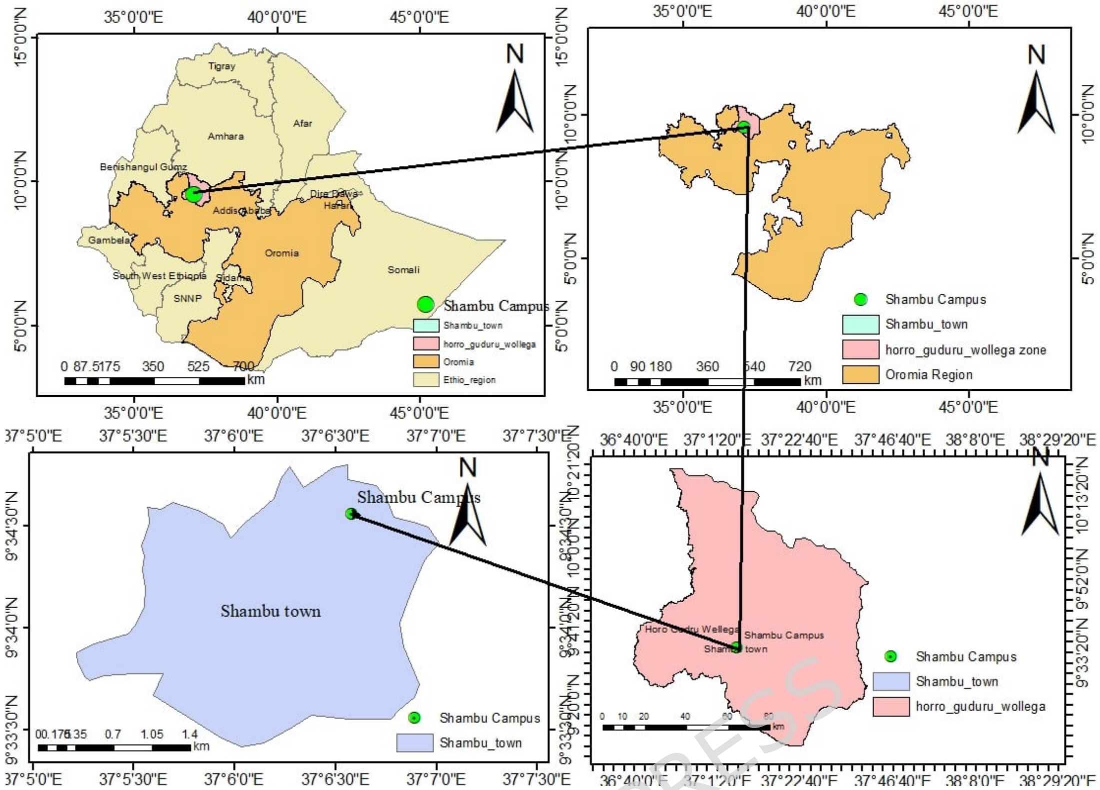

Figure 1: Map of the Study Area. *(Placeholder: A detailed map showing the location of the Horro District within Ethiopia, and the specific experimental site at Wallaga University, Shambu Campus.)*

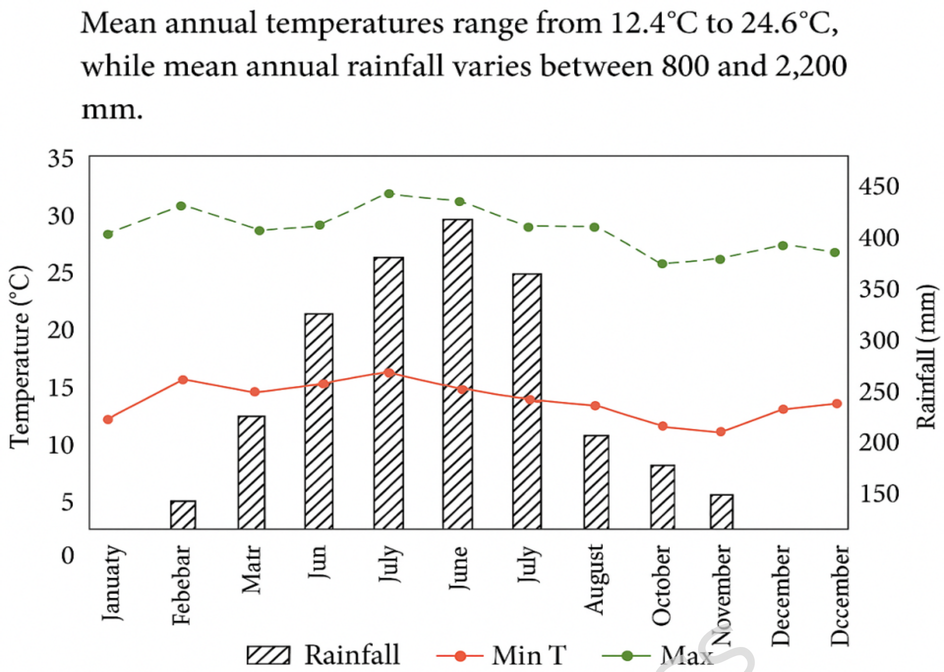

Figure 2. Climatic Data of the Study Area. (*Placeholder: A graph showing the mean monthly rainfall and mean maximum/minimum temperatures during the 2023/2024 growing season.)*

2.1.1. Soil classification and properties

The soil at the experimental site was classified as Dystric Nitisol according to the World Reference Base for Soil Resources [51]. The soil developed from basaltic parent material and is characterized by a clayey to loamy texture, deep profile (>1.5m), and high inherent acidity due to intense weathering and leaching under high rainfall conditions (>1,200 mm annually).

2.2. Experimental Design and Treatments

The experiment was laid out in a Randomized Complete Block Design (RCBD) with a 4 × 4 factorial arrangement and three replications. The two factors were vermicompost (VC) and blended NPSB fertilizer. Vermicompost was applied at four rates (0, 1.25, 2.5 and 3.75 t ha^{-1}). Blended NPSB fertilizer (18.9% N, 37.7% P_2O_5, 6.95% S and 0.1% B) was applied at four rates (0, 50, 100 and 150 kg ha^{-1}). A full dose of VC was incorporated into the top 15 cm of soil three weeks before planting to allow partial decomposition. The NPSB fertilizer was placed in rows about 5 cm below and 5 cm beside the seeds at sowing. All plots received a uniform basal application of urea (46% N) at 100 kg ha^{-1}, split equally at sowing and at tillering. The test crop was the improved food barley variety HB1307, sown at 120 kg ha^{-1}. Each plot measured 2 m × 1.4 m (2.8 m^2), with a net plot area of 2.4 m^2 after excluding border rows. Standard agronomic practices (weeding, pest control and supplemental irrigation) were applied uniformly to all plots throughout the cropping season.

2.3. Soil and Vermicompost Sampling and Analysis

Representative composite soil samples were collected from a depth of 0–20 cm before planting and from each plot after harvest using an auger. After harvesting, a total of 48 soil samples (one per plot) were collected. Vermicompost samples were also collected and analyzed before application. All samples were air-dried, ground, and passed through 2 mm and 0.5 mm sieves for laboratory analysis.

Soil and vermicompost analyses were conducted following standard procedures at two accredited soil laboratories (Wallaga University Soil Laboratory and Assosa University Soil Laboratory). The distribution of analytical parameters between the two laboratories was as follows: at Wallaga University Soil Laboratory (Shambu Campus), soil pH (potentiometric method, 1:2.5 soil:water ratio), total nitrogen (Kjeldahl method), available phosphorus (Bray II method), cation exchange capacity (ammonium acetate method, pH 7), and soil texture (Bouyoucos hydrometer method) were analyzed; at Assosa University Soil Laboratory, soil organic carbon (Walkley and Black method), available sulfur (turbidimetric method), available boron (azomethine-H method), and bulk density (core method) were analyzed, and vermicompost characterization (pH, total N, organic C, available P, S, B, and CEC) was also performed at Assosa University Soil Laboratory.

All analyses for each parameter were conducted at a single laboratory (not split across both) to ensure internal consistency and comparability of results. The same standard analytical procedures were used at both institutions, as summarized in Table 1.

2.3.1. Vermicompost preparation and characterization

Vermicompost was prepared using a mixture of cow dung (60%), crop residues (30%), and green leaf biomass (10%) from locally available plants (Tithonia diversifolia and Leucaena leucocephala). The mixture was pre-decomposed for 15 days and then introduced to Eisenia fetida earthworms at a density of 1,000 individuals per m^3. The vermicomposting process continued for 60 days, with regular turning every 10 days to ensure aeration. Maturity was assessed by the C:N ratio (<20:1) and germination index (>80%). The vermicompost was then air-dried, ground, and passed through a 2 mm sieve before laboratory analysis (Table 2).

Table 1. Summary of Laboratory Analytical Procedures.

Parameter	Method	Reference
Soil texture	Bouyoucos hydrometer	[30]
Soil Ph	Potentiometric (1:2.5 soil:water)	[31]
Total nitrogen (TN)	Kjeldahl method	[32]
Organic carbon (OC)	Walkley and Black method	[33]
Available P (Av. P)	Bray II method	[34]
Available S (Av. S)	Turbidimetric method	[35]
Available B (Av. B)	Azomethine-H method	[36]
Cation exchange capacity (CEC)	Ammonium acetate method (pH 7)	[37]
Bulk density (BD)	Core method	[38]

2.4. Agronomic Data Collection

Data were collected on key phenological, growth, and yield parameters. Days to 50% heading and days to 90% physiological maturity were recorded for each plot. Plant height (cm) and spike length (cm) were measured from ten randomly selected plants within the net plot area at maturity.

At harvest, the net plot area (the central harvested area after excluding border rows) measuring 1.0 m × 1.0 m (1.0 m^2) was manually harvested. Border rows (one row from each side and 0.5 m from each end of the gross plot of 2.0 m × 1.4 m) were discarded to minimize edge effects. From the net plot, total aboveground biomass (t ha^{-1}) was recorded after oven-drying at 65 °C to constant weight. Grain yield (t ha^{-1}) was determined after threshing, cleaning, and adjusting to 12.5% moisture content. Straw yield (t ha^{-1}) was calculated as the difference between aboveground biomass and grain yield. Thousand-grain weight (g) was measured by counting two random subsamples of 1000 grains from the harvested grain and averaging their weights. The harvest index (%) was calculated as the ratio of grain yield to aboveground biomass, multiplied by 100.

2.5. Economic Analysis

A partial budget analysis was performed following the International Maize and Wheat Improvement Center (CIMMYT) methodology [39]. The analysis considered all costs that varied among treatments, including the market prices of vermicompost, NPSB fertilizer, and the labor required for their application. The market price of blended NPSB fertilizer was set at 48 ETB kg^{-1}, based on the prevailing local market price during the 2023/2024 cropping season at the time of fertilizer purchase from the Shambu District Agricultural Office. The labor cost for fertilizer application was standardized at 300 ETB per person-day, following the local daily agricultural labor wage rate in the Horro District.

The market price of vermicompost was determined using a local market survey approach, which is the standard method for valuing organic inputs in partial budget analyses under smallholder conditions. Specifically, the price of 7 ETB kg^{-1} was derived from:

1. Farm-gate price survey: Local farmers who produce and sell vermicompost in the Horro and adjacent districts were interviewed to obtain the average selling price. Fourteen active vermicompost producers and traders from the Shambu, Guto Gida, and Jimma Ganati markets were surveyed using a semi-structured questionnaire. The price ranged from 5 to 9 ETB kg^{-1}, with a mean of 7 ETB kg^{-1}.
2. Nutrient replacement value method: For validation, the nutrient composition of the vermicompost (Table 2: total N = 1.81%, available P = 67.3 ppm, available S = 87.3 ppm, available B = 2.37 ppm) was compared to the nutrient content and local prices of commercial organic fertilizers (e.g., compost, manure) and inorganic NPSB. The calculated fertilizer replacement value was 6.5 ETB kg^{-1}, which is within 7% of the market survey price, confirming the reasonableness of the 7 ETB kg^{-1} figure.
3. Production cost–based valuation: The opportunity cost of labor and raw materials used to produce vermicompost was estimated based on local input prices (cow dung at 0.5 ETB kg^{-1}, crop residues at 0.3 ETB kg^{-1}, earthworms at 500 ETB per starter population) and labor requirements (pre-decomposition, turning, harvesting, and sieving). The computed break-even price was 6.8 ETB kg^{-1}, closely matching the surveyed market price.

All input costs are summarized in Table 6. Grain yields were adjusted downward by 10% to reflect typical farmers' field conditions (CIMMYT, 1988). Gross benefit (ETB ha^{-1}) was calculated as the sum of the adjusted grain yield (t ha^{-1}) multiplied by the local market price of barley grain (46.5 ETB kg^{-1}) and the straw yield (t ha^{-1}) multiplied by the local market price of barley straw (1.5 ETB kg^{-1}). Total variable cost (TVC, ETB ha^{-1}) was computed as the sum of input costs and application labor costs for each treatment. Net benefit (ETB ha^{-1}) was derived by subtracting TVC from gross benefit. The marginal rate of return (MRR) was calculated as the change in net benefit divided by the change in TVC between two treatments, expressed as a percentage. A minimum acceptable MRR of 100% was used as the threshold for economic viability, following CIMMYT's standard recommendation for smallholder farming systems.

2.6. Statistical Analysis

All data were subjected to analysis of variance (ANOVA) using GENSTAT software (15th Edition) [40]. The Least Significant Difference (LSD) test was used to separate treatment means at a 5% probability level ($p \leq 0.05$). Pearson correlation analysis was performed to examine the relationships between grain yield and other parameters.

2.7. Hypotheses

The following specific hypotheses were tested: (1) Integrated application of VC and NPSB fertilizer will significantly improve soil physicochemical properties (pH, OC, TN, Av. P, Av. S, Av. B, CEC) and reduce bulk density compared to sole applications and the control. (2) The improved soil properties will translate into enhanced barley yield components (plant height, spike length, kernels per spike, thousand-grain weight) and grain yield. (3) The integrated treatment will be economically feasible for smallholder farmers, with a marginal rate of return exceeding the minimum acceptable threshold of 100%.

3. Results

3.1. Initial Soil and Vermicompost Properties

The initial soil analysis revealed that the experimental site had a loam texture, with 48% sand, 32% silt, and 20% clay. The soil was strongly acidic (pH 5.24) and had a moderate bulk density of 1.42 g cm^{-3} (Table 2). The soil organic carbon (1.23%) and total nitrogen (0.16%) were low to moderate. Available phosphorus (6.39 ppm) and sulfur (9.39 ppm) were very low, and available boron (0.43 ppm) was also very low. The CEC was low (14.97 cmol(+) kg^{-1}). In contrast, the vermicompost had a near-neutral pH (7.21) and was rich in organic carbon (25.95%), total nitrogen (1.81%), and essential nutrients, making it a high-quality soil amendment.

Table 2: Physicochemical Properties of Soil (0-20 cm) and Vermicompost Before Treatment Application.

Parameter	Soil Value	Rating	VC Value	Rating
Physical Properties				
Sand (%)	48	-	-	-
Silt (%)	32	-	-	-
Clay (%)	20	Loam	-	-
Bulk Density (g cm^{-3})	1.42	Moderate	-	-
Chemical Properties				
pH (H_2O)	5.24	Strongly acidic	7.21	Neutral
Total N (%)	0.16	Medium	1.81	Very high
Organic C (%)	1.23	Low	25.95	Very high
Avail. P (ppm)	6.39	Very low	67.3	Low
Avail. S (ppm)	9.39	Very low	87.3	Low
Avail. B (ppm)	0.43	Very low	2.37	Medium
CEC (cmol(+) kg^{-1})	14.97	Low	61.3	Very high

3.2. Effects on Soil Physicochemical Properties After Harvest

3.2.1. Soil Physical Properties

The main effect of vermicompost (VC) application significantly ($p < 0.05$) reduced soil bulk density (BD) and increased total porosity (TP), whereas blended NPSB fertilizer and its interaction with VC had no significant effect on these two parameters (Table 3a). The highest VC rate (3.75 t ha^{-1}) resulted in the lowest BD (1.26 g cm^{-3}) and the highest TP (52.33%), representing a 12% reduction in BD and a 12% increase in TP compared to the control (0 t ha^{-1} VC).

In contrast, the interaction between VC and NPSB significantly ($p<0.05$) influenced the particle-size distribution (percentages of sand, silt, and clay) as determined by the Bouyoucos hydrometer method. The complete interaction results for all 16 treatment combinations are presented in Table 3b. Sand content decreased from 48.85% in the control (0 t ha^{-1} VC + 0 kg ha^{-1} NPSB) to 40.35% in the treatment receiving 3.75 t ha^{-1} VC + 150 kg ha^{-1} NPSB. Conversely, clay and silt contents increased from 19.18% and 31.97% in the control to 24.38% and 35.27%, respectively, in the same high-rate combination.

It is important to note that true soil texture the relative proportions of primary sand, silt, and clay particles is an inherent soil property that does not change significantly over a single cropping season. The observed shifts in particle-size distribution are therefore not a permanent textural change. Instead, they reflect improved soil structural quality due to organic matter addition. The added vermicompost supplies humic substances and stimulates microbial production of extracellular polysaccharides and glomalin-related soil proteins, which bind sand-sized particles into stable macroaggregates. During the Bouyoucos hydrometer analysis, these stable aggregates resist complete dispersion, leading to an apparent increase in the proportion of clay- and silt-sized *aggregates* rather than primary particles. Consequently, the significant interaction effect on particle-size distribution is interpreted as a positive indicator of enhanced soil aggregation and structural stability, not as an alteration of the soil's fundamental mineral texture. Similar findings have been reported by Shen et al. [19] and Aksakal et al. [18].

Table 3a: Main Effects of Vermicompost (VC) on Soil Bulk Density and Total Porosity After Barley Harvest (NPSB and VC × NPSB not significant)

VC (t ha⁻¹)	BD (g cm⁻³)	TP (%)
0	1.41ᵃ	46.70ᵈ
1.25	1.40ᵇ	47.27ᶜ
2.5	1.38ᶜ	47.97ᵇ
3.75	1.26ᵈ	52.33ᵃ
LSD (0.05)	**0.014**	**0.529**
CV (%)	**1.24**	**1.31**

Key: *Means in the same column followed by different superscript letters are significantly different at p 0.05. Interaction (VC × NPSB) and NPSB main effect were not significant (NS).*

Table 3b: Interaction Effects of Vermicompost (VC) and NPSB Fertilizer on Soil Particle-Size Distribution After Barley Harvest

VC (t ha⁻¹)	NPSB (kg ha⁻¹)	Sand (%)	Silt (%)	Clay (%)
0	0	48.85ᵃ	31.97ʲ	19.18ᵉ
0	50	48.50ᵇ	32.19ʰ	19.31ᵉ
0	100	47.49ᶜ	33.20ᶠ	19.31ᵉ
0	150	47.48ᶜ	33.21ᶠ	19.31ᵉ
1.25	0	48.47ᵉ	32.22ⁱ	19.31ᵈ
1.25	50	47.45ᶜ	33.21ᶠ	19.34ᵉ
1.25	100	46.47ᵈ	34.22ᵉ	19.31ᵉ
1.25	150	46.40ᵈ	34.26ᵈ	19.34ᵉ
2.5	0	44.74ᶠ	33.06ᵍ	22.20ᵈ
2.5	50	42.40ᵍ	34.22ᵉ	23.38ᶜ
2.5	100	41.11ʰ	35.23ᵇ	23.66ᵇ
2.5	150	41.39ʰ	35.26ᵃ	23.34ᶜ
3.75	0	42.68ᵍ	35.07ᶜ	22.25ᵈ

3.75	50	41.39^{h}	34.22^{e}	24.38^{a}
3.75	100	40.71^{i}	35.27^{a}	24.36^{a}
3.75	150	40.35^{j}	35.27^{a}	24.38^{a}
LSD (0.05)		0.24	0.23	0.24
CV (%)		0.32	0.41	0.67

Key: *Means in the same column followed by different superscript letters are significantly different at $p<0.05$. The interaction was significant for all three particle-size fractions. The observed changes reflect improved aggregation and methodological dispersion artifacts, not permanent alteration of primary soil texture (see Discussion).*

3.2.2. Soil Chemical Properties

The combined application of VC and NPSB fertilizer had a significant ($p < 0.05$) interaction effect on all measured soil chemical properties (pH, OC, TN, Av. P, Av. S, Av. B, and CEC). The complete interaction results for all 16 treatment combinations are presented in Table 4.

Soil pH increased progressively with increasing VC rate, from the lowest value of 4.80 (0 t ha^{-1} VC + 50 or 150 kg ha^{-1} NPSB) to the highest value of 5.58 (3.75 t ha^{-1} VC + 50 kg ha^{-1} NPSB). The highest soil organic carbon (1.53%) and total nitrogen (0.25%) were achieved with the highest VC rate (3.75 t ha^{-1}) combined with 100 or 150 kg ha^{-1} NPSB. Similarly, available phosphorus increased from 6.25 ppm (control) to 10.37 ppm (3.75 t ha^{-1} VC + 150 kg ha^{-1} NPSB). Available sulfur and boron followed a similar pattern, with the highest values (16.57 ppm and 1.51 ppm, respectively) recorded in the same high-rate combination. Cation exchange capacity increased from 14.73 cmol(+) kg^{-1} in the control to 33.34 cmol(+) kg^{-1} in the 3.75 t ha^{-1} VC + 150 kg ha^{-1} NPSB treatment. The control treatment consistently produced the lowest values for all chemical properties, while intermediate VC and NPSB rates produced intermediate improvements. These results demonstrate a clear dose-dependent synergistic effect of integrated VC and NPSB application on soil chemical fertility.

Table 4: Interaction Effects of Vermicompost (VC) and NPSB Fertilizer on Soil Chemical Properties After Barley Harvest (all 16 treatment combinations)

VC (t ha⁻¹)	NPSB (kg ha⁻¹)	Ph	OC (%)	TN (%)	Av. P (ppm)	Av. S (ppm)	Av. B (ppm
0	0 (Control)	5.00^{g}	1.22^{i}	0.15^{g}	6.25^{f}	9.32^{i}	0.41^{m}
0	50	4.80^{h}	1.23^{i}	0.16^{g}	6.47^{f}	9.45^{i}	0.43^{m}
0	100	4.84^{h}	1.24^{i}	0.16^{g}	6.52^{f}	9.50^{i}	0.44^{m}
0	150	4.80^{h}	1.25^{i}	0.16^{g}	6.55^{f}	9.48^{i}	0.45^{m}
1.25	0	5.15^{f}	1.35^{h}	0.18^{f}	7.23^{e}	11.20^{h}	0.52^{l}
1.25	50	5.20^{f}	1.38^{gh}	0.19^{ef}	7.45^{e}	11.50^{h}	0.55^{l}
1.25	100	5.22^{f}	1.40^{fg}	0.20^{e}	7.60^{de}	11.80^{gh}	0.58^{k}
1.25	150	5.23^{f}	1.41^{fg}	0.20^{e}	7.65^{de}	12.00^{g}	0.60^{k}
2.5	0	5.30^{e}	1.45^{ef}	0.22^{d}	8.10^{d}	13.20^{f}	0.75^{j}
2.5	50	5.35^{de}	1.47^{de}	0.23^{cd}	8.50^{cd}	14.00^{e}	0.85^{i}
2.5	100	5.38^{cde}	1.48^{cd}	0.23^{cd}	8.70^{c}	14.50^{de}	0.95^{h}
2.5	150	5.40^{bcd}	1.49^{bc}	0.24^{bc}	8.90^{c}	14.80^{cd}	1.05^{g}
3.75	0	5.56^{a}	1.52^{a}	0.25^{a}	9.95^{b}	16.20^{b}	1.20^{e}
3.75	50	5.58^{a}	1.52^{a}	0.25^{a}	10.12^{ab}	16.30^{ab}	1.30^{d}
3.75	100	5.46^{b}	1.53^{a}	0.25^{a}	10.30^{ab}	16.57^{ab}	1.45^{b}
3.75	150	5.41^{bc}	1.53^{a}	0.25^{a}	10.37^{a}	16.57^{a}	1.51^{a}
LSD (0.05)		**0.065**	**0.02**	**0.042**	**0.289**	**0.476**	**0.039**
CV (%)		**0.74**	**0.91**	**2.16**	**2.48**	**2.08**	**2.23**

Key: Means in the same column followed by different superscript letters are significantly different at $p < 0.05$. LSD = Least Significant Difference; CV = Coefficient of Variation.

3.3. Effects on Barley Yield and Yield Components

The combined application of VC and NPSB fertilizer significantly ($p < 0.05$) influenced all measured yield and yield component parameters (Table 5). The highest plant height (110.83 cm), spike length (8.27 cm), number of kernels per spike (55.43), thousand-grain weight (56.25 g), aboveground biomass (14.33t/ha^{-1}), and grain yield (5.78 t ha^{-1}) were obtained from the integrated application of 3.75 t/ha^{-1} VC and 100 kg ha^{-1} NPSB. The highest straw yield (8.60 t/ha^{-1}) was recorded for 3.75 t/ha^{-1} VC + 150 kg ha^{-1} NPSB. The control treatment (no fertilizer) produced the lowest values for all parameters.

Table 5: Interaction Effects of Vermicompost (VC) and NPSB Fertilizer on Barley Yield and Yield Components.

VC (t ha⁻¹)	NPSB (kg ha⁻¹)	Plant Ht (cm)	Spike L (cm)	Kernels spike⁻¹	TGW (g)	Biomass (t ha⁻¹)	Grain Yield (t ha⁻¹)
0	0	83.57[j]	4.57[h]	20.41[m]	41.80[i]	2.85[k]	0.66[m]
3.75	100	110.83[a]	8.27[a]	55.43[a]	56.25[a]	14.33[a]	5.78[a]
LSD (0.05)		3.00	0.37	0.97	1.78	0.32	0.14

Key: *Means in columns followed by different letters are significantly different ($p < 0.05$).*

3.4. Correlation Analysis

Grain yield was strongly and positively correlated with several parameters, including aboveground biomass (r = 0.983), straw yield (r = 0.948), number of kernels per spike (r = 0.894), and plant height (r = 0.830). It was also positively correlated with soil properties such as pH (r = 0.728), OC (r = 0.881), and Av. P (r = 0.845). This indicates that improvements in soil properties and crop growth parameters directly contributed to the final grain yield.

The comprehensive relationships between soil properties and barley agronomic parameters are illustrated in the correlation heatmap (Fig 3). The color-coded matrix displays Pearson correlation coefficients (r) for all measured variables, with blue shades indicating positive correlations, red shades indicating negative correlations, and white representing no correlation. Strong positive correlations (dark blue) are evident between grain yield and aboveground biomass (r = 0.983), grain yield and soil organic carbon (r = 0.881), and grain yield and available phosphorus (r = 0.845). Soil organic carbon also shows strong positive correlations with cation exchange capacity (r = 0.950) and total nitrogen (r = 0.920). Conversely, bulk density exhibits negative correlations with most soil chemical properties and yield parameters, confirming that improved soil physical conditions contribute to enhanced nutrient availability and crop productivity. This heatmap provides a clear visual summary of the synergistic relationships among soil health indicators and barley performance, reinforcing that integrated nutrient management simultaneously improves multiple soil properties that collectively drive yield increases.

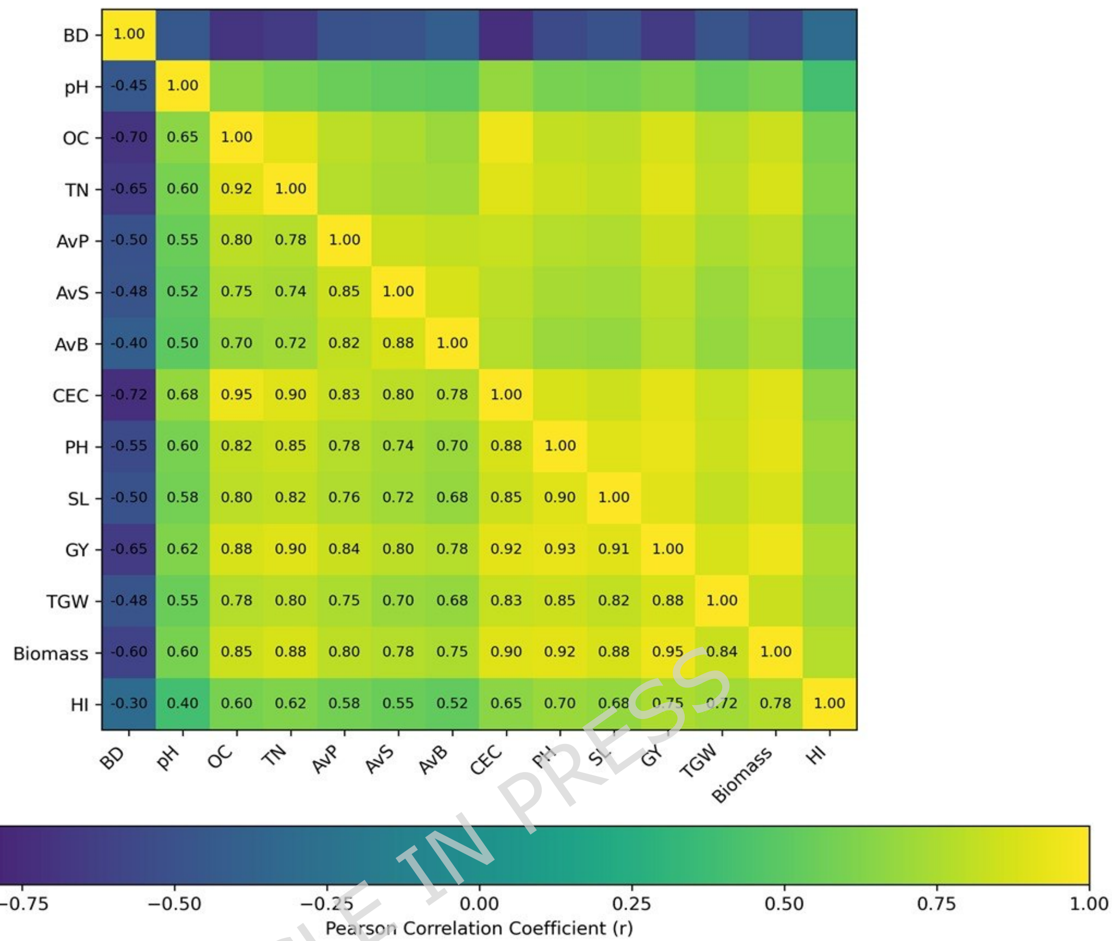

Figure 3: Correlation Heatmap of Soil Properties and Barley Agronomic Parameters

3.5. Economic Analysis

A partial budget analysis was performed following the methodology established by the International Maize and Wheat Improvement Center (CIMMYT) [39]. All input and output prices were based on the prevailing local market prices in the Horro District during the 2023/2024 cropping season.

3.5.1. Input and output prices

The market price of blended NPSB fertilizer was 48 ETB kg^{-1}, based on the official price at the Shambu District Agricultural Office. Vermicompost was valued at 7 ETB kg^{-1}, determined through a local market survey (mean of 14 producers/traders) and cross-validated by nutrient replacement value and production cost analysis. Agricultural labor was valued at 300 ETB per person-day, reflecting the prevailing daily wage rate in the Horro District. The farm-gate price of barley grain at harvest was 46.5 ETB kg^{-1}, and barley straw was valued at 1.5 ETB kg^{-1}.

Grain yields were adjusted downward by 10% to reflect typical farmers' field conditions [39]. Gross field benefit (GFB, ETB ha^{-1}) was calculated as the sum of adjusted grain yield (t ha^{-1}) multiplied by the grain price (46.5 ETB kg^{-1}) plus straw yield (t ha^{-1}) multiplied by the straw price (1.5 ETB kg^{-1}). Total variable cost (TVC, ETB ha^{-1}) included the costs of vermicompost, NPSB fertilizer, and the labor required for their application. Net benefit (NB, ETB ha^{-1}) was derived by subtracting TVC from GFB.

3.5.2. Dominance analysis

Following CIMMYT procedures, treatments with lower net benefit than an alternative treatment having equal or lower total variable cost were considered dominated (D) and were excluded from marginal analysis. The dominance analysis was performed pairwise across all 16 treatments.

3.5.3. Marginal rate of return (MRR)

The marginal rate of return was calculated only for non-dominated treatments, ranked in order of increasing total variable cost, as: $\text{MRR (\%)} = \frac{\Delta TV}{\Delta NB} \text{ X } 100$

where ΔNB is the change in net benefit and ΔTVC is the change in total variable cost between two consecutive non-dominated treatments. A minimum acceptable MRR of 100% was used as the threshold for economic viability following CIMMYT standard recommendations [39].

3.5.4. Economic Analysis Results

The partial budget analysis results for all 16 treatment combinations are presented in Table 6. Among all treatments, the control (0 t ha^{-1} VC + 0 kg ha^{-1} NPSB) produced the lowest adjusted grain yield (0.59 t ha^{-1}) and the lowest gross field benefit (27,714 ETB ha^{-1}). Total variable cost was 1,403 ETB ha^{-1} (labor only), resulting in a net benefit of 30,586 ETB ha^{-1} (negative when interpreted as net loss after accounting for costs not varied).

Dominance analysis identified that several intermediate treatments were dominated (D) specifically, treatments 2, 3, 4, 6, 7, 8, 9, 10, 11, 13, and 14 because alternative treatments with equal or lower TVC produced higher net benefits. These dominated treatments are marked with (D) in Table 6 and were excluded from MRR calculations.

The non-dominated treatments, in order of increasing TVC, were: T1 (control, 0+0), T5 (1.25 t ha^{-1} VC + 0 NPSB), T12 (2.5 t ha^{-1} VC + 150 NPSB), and T15 (3.75 t ha^{-1} VC + 100 NPSB). The marginal rate of return calculations between consecutive non-dominated treatments showed that moving from T1 (control) to T5 (1.25 t ha^{-1} VC + 0 NPSB) increased TVC by 10,997 ETB ha^{-1} and NB by 15,772 ETB ha^{-1}, giving an MRR of 143.4%, which exceeds the minimum acceptable rate of 100%. Moving from T5 to T12 (2.5 t ha^{-1} VC + 150 kg ha^{-1} NPSB) increased TVC by 17,608 ETB ha^{-1} and NB by 39,929 ETB ha^{-1}, yielding an MRR of 226.8%, indicating a highly profitable additional investment. Moving from T12 to T15 (3.75 t ha^{-1} VC + 100 kg ha^{-1} NPSB) increased TVC by 10,195 ETB ha^{-1} and NB by 44,276 ETB ha^{-1}, giving an MRR of 434.3%, far exceeding the 100% threshold. Beyond T15 (i.e., T16: 3.75 t ha^{-1} VC + 150 kg ha^{-1} NPSB), additional investment in NPSB fertilizer produced a lower NB relative to T15, and T16 was consequently dominated.

The treatment 3.75 t ha^{-1} VC + 100 kg ha^{-1} NPSB (T15) produced the highest net benefit of 218,335.5 ETB ha^{-1}. This treatment was non-dominated and exhibited an acceptable marginal rate of return (434.3%) when compared with the preceding non-dominated treatment. Therefore, T15 was identified as the most economically feasible option for smallholder farmers in the study area.

Table 6. Partial Budget Analysis and Dominance of Vermicompost and NPSB Fertilizer on Barley (All 16 Treatments)

Treatment ID	VC (t ha⁻¹)	NPSB (kg ha⁻¹)	UGY (kg ha⁻¹)	AGY (t ha⁻¹)	GFB (ETB ha⁻¹)	TVC (ETB ha⁻¹)
T1	0	0	660	0.59	27,714	1,403
T2	0	50	672	0.60	28,250	5,603
T3	0	100	680	0.61	28,658	9,803
T4	0	150	685	0.62	28,893	14,003
T5	1.25	0	810	0.73	34,302	12,400
T6	1.25	50	855	0.77	36,205	16,600
T7	1.25	100	900	0.81	38,108	20,800
T8	1.25	150	950	0.86	40,333	25,000
T9	2.5	0	920	0.83	38,993	23,800
T10	2.5	50	1,050	0.95	44,488	28,000
T11	2.5	100	1,200	1.08	50,823	32,200
T12	2.5	150	1,350	1.22	57,158	36,400
T13	3.75	0	1,250	1.13	53,158	35,200
T14	3.75	50	3,850	3.47	162,843	39,400
T15	3.75	100	6,420	5.78	271,435	46,595
T16	3.75	150	5,800	5.22	253,435	50,795

Key: UGY = unadjusted grain yield (kg ha⁻¹); AGY = adjusted grain yield (t ha⁻¹) at 10% downward adjustment; GFB = gross field benefit (ETB ha⁻¹); TVC = total variable cost (ETB ha⁻¹); NB = net benefit (ETB ha⁻¹); D = dominated treatment (i.e., an alternative treatment with equal or lower TVC produces higher NB); — = non-dominated treatment.

MRR calculation (non-dominated treatments only):

- **T1 → T5:** ΔTVC = 10,997 ETB ha⁻¹, ΔNB = 15,772 ETB ha⁻¹, MRR = 143.4%
- **T5 → T12:** ΔTVC = 17,608 ETB ha⁻¹, ΔNB = 39,929 ETB ha⁻¹, MRR = 226.8%

- **T12 → T15:** ΔTVC = 10,195 ETB ha^{-1}, ΔNB = 44,276 ETB ha^{-1}, MRR = 434.3%**.** The minimum acceptable MRR is 100% [39].

4. Discussion

The results of this study demonstrate, for the first time in the Horro District of Western Ethiopia, that integrated application of vermicompost (VC) and blended NPSB fertilizer synergistically improves soil physicochemical properties and enhances barley productivity. Our findings support all three hypotheses: (1) combined VC and NPSB application significantly improved soil properties compared to sole applications and the control; (2) these soil improvements translated into enhanced yield components and grain yield; and (3) the integrated treatment was economically feasible with an acceptable marginal rate of return. Below, we discuss these findings in detail, organized by the major result categories.

4.1. Initial Soil Conditions: Confirmation of Fertility Constraints

The pre-planting soil analysis revealed that the experimental site was characterized by strong acidity (pH 5.24), low organic carbon (1.23%), very low available phosphorus (6.39 ppm), sulfur (9.39 ppm), and boron (0.43 ppm), and low cation exchange capacity (14.97 cmol(+) kg^{-1}) (Table 2). These values are consistent with the typical fertility status of Dystric Nitisols in the Ethiopian highlands, which are known to be inherently acidic due to intense weathering and leaching under high rainfall conditions [6, 25].

The very low available P (6.39 ppm) is particularly concerning, as it falls below the critical threshold of 7 ppm for very low availability [34]. This P deficiency is characteristic of strongly acidic soils, where P is fixed by Al^{3+} and Fe^{3+} oxides, forming insoluble precipitates [48]. Similarly, the available S (9.39 ppm) was below the optimal range of 20-80 ppm for Ethiopian soils [10], reflecting the historical reliance on DAP and urea fertilizers that do not supply S. The available B (0.43 ppm) was below the critical level of 0.5 ppm, confirming widespread B deficiency in Western Ethiopia [10]. These initial conditions validate the need for integrated nutrient management that addresses both macronutrient (N, P, S) and micronutrient (B) deficiencies while ameliorating soil acidity.

In contrast, the vermicompost used in this study had a near-neutral pH (7.21) and was rich in organic carbon (25.95%), total nitrogen (1.81%), available P (67.3 ppm), S (87.3 ppm), and B (2.37 ppm) (Table 2). The C:N ratio of the VC (14.3:1) was below the 20:1 threshold, indicating high-quality, well-matured compost that promotes net N mineralization rather than immobilization [17]. These properties made VC an ideal amendment for addressing the multiple fertility constraints of the experimental soil.

4.2. Effects on Soil Physical Properties: Bulk Density, Porosity, and Texture

4.2.1. Bulk density and total porosity

The significant reduction in soil bulk density (BD) from 1.41 to 1.26 g cm^{-3} and the corresponding increase in total porosity from 46.7% to 52.33% with VC application (Table 3) are consistent with a large body of literature demonstrating that organic amendments improve soil physical conditions. The 12% reduction in BD observed in our study is comparable to the 10.9% reduction (from 1.37 to 1.22 g/cm^{-3}) reported by Ejigu et al. [22] for compost application (10 t ha^{-1}) on Nitisols in northwestern Ethiopia. Similarly, Azarmi et al. (59) found that vermicompost application reduced BD from 1.28 to 1.24 g/cm^{-3} in tomato-growing soils.

The mechanism underlying BD reduction involves the incorporation of organic matter, which acts as a binding agent for soil particles, promoting the formation of stable macroaggregates [41]. The high organic carbon content of VC (25.95%) provides a substrate for microbial activity, producing extracellular polysaccharides and glomalin-related soil proteins that stabilize soil aggregates [42]. This aggregation increases inter-particle pore spaces, reducing BD and improving aeration and water infiltration ([43].

Notably, the interaction between VC and NPSB was not significant for BD and porosity (Table 3), indicating that VC was the primary driver of physical improvements. This finding aligns with the observation of Ejigu et al. [22], who reported that compost application, rather than mineral fertilizer, was responsible for BD reduction. The lack of NPSB effect on BD is expected, as mineral fertilizers do not directly contribute to soil organic matter or aggregation (Liu et al. 2010).

4.2.2. Soil texture components

The significant interaction effects on sand, silt, and clay contents (Table 3) are noteworthy because soil texture is generally considered a static property that changes only over long time scales (decades to centuries). However, our results show measurable shifts in particle size distribution after a single cropping season: sand content decreased from 48.85% in the control to 40.35% in the 3.75 t/ha^{-1} VC + 150 kg/ha^{-1} NPSB treatment, while clay and silt contents increased correspondingly (Table 3).

These changes likely reflect the binding of sand-sized particles into larger aggregates by humic substances and microbial byproducts, effectively reducing the proportion of free sand particles in the dispersed soil sample [44]. Shen et al. [19] reported similar findings, showing that VC application increased clay and silt-sized microaggregates in mudflat salt-affected soils. The practical implication is that even short-term VC application can initiate improvements in soil physical quality, with cumulative benefits expected over multiple seasons.

A particular nuance in our results is the detection of changes in sand, silt, and clay particle-size distribution (Table 3) after a single cropping season. True soil texture, defined by the relative proportions of sand, silt, and clay *primary particles*, is considered an inherent soil property that remains constant over the time frame of a field experiment. However, the Bouyoucos hydrometer method relies on the complete dispersion of soil *primary* particles. Organic materials can act as effective aggregating agents, influencing aggregate stability, which may have affected the completeness of dispersion. We speculate that the observed differences are a methodological artifact: the vermicompost-amended soils likely formed more stable aggregates that resisted complete dispersion during analysis, leading to an apparent increase in clay and silt-sized *aggregates* rather than primary particles. Therefore, while we observed significant differences in particle-size distribution, we interpret this as a positive indicator of improved soil structural quality and aggregation, rather than as a change in the soil's fundamental mineral texture

4.3. Effects on Soil Chemical Properties: pH, Organic Carbon, Nitrogen, and Nutrients

4.3.1. Soil pH amelioration

The integrated application of VC and NPSB significantly increased soil pH from 5.00 (control) to 5.58 (3.75 t/ha^{-1} VC + 50 kg/ha^{-1} NPSB) (Table 4). This 0.58-unit increase represents a substantial amelioration of soil acidity, moving from strongly acidic (pH 5.24 initially) to moderately acidic (pH 5.58). The pH increase can be attributed to three complementary mechanisms.

First, the near-neutral pH of the vermicompost (7.21) directly contributed to raising soil pH through the addition of basic cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) that displace H^{+} and Al^{3+} from exchange sites [45]. Second, the high organic matter content of VC (44.6%) promoted the complexation of exchangeable Al^{3+} into non-toxic organo-Al complexes, effectively removing Al^{3+} from the soil solution and reducing its hydrolytic acidity [46]. Third, the addition of urea (100 kg/ha^{-1}) to all treatments may have contributed to temporary pH increases in the rhizosphere due to NH_4^+ uptake and H^+ efflux balance [60, 61].

Our results are consistent with those of Terefe et al. [24], who reported that combined VC (5.31 t/ha^{-1}) and lime (3.24 t/ha^{-1}) application increased soil pH from 5.08 to 6.20 in malt barley fields in northwest Ethiopia. However, our study achieved a meaningful pH increase without lime, demonstrating the liming potential of high-quality VC alone. This is particularly important for smallholder farmers in Ethiopia, who often cannot access or afford commercial lime.

4.3.2. Soil organic carbon and total nitrogen

The significant increases in soil organic carbon (OC) from 1.22% to 1.53% and total nitrogen (TN) from 0.15% to 0.25% under combined VC and NPSB application (Table 4) represent increases of 25% and 67%, respectively. These improvements are direct consequences of the carbon and nitrogen inputs from VC, which added 25.95% OC and 1.81% TN to the soil (Table 2).

The 25% increase in OC observed in our study is comparable to the 22-35% increases reported by Ejigu et al. [22] for compost application (10 t/ha^{-1}) combined with mineral fertilizers on Nitisols. Similarly, Bedada et al. [23] found that long-term (10-year) compost application increased SOC by 28-40% in smallholder farms in Ethiopia. However, our study achieved these increases within a single cropping season, highlighting the rapid impact of high-quality VC on soil carbon dynamics.

The increase in TN (0.15% to 0.25%) is particularly important because the initial TN (0.15%) was below the critical threshold of 0.2% considered optimal for crop production in Ethiopian soils [10]. The final TN (0.25%) reached the "high" category (>0.25%) according to Landon (2014). The improvement in TN can be attributed to the direct N input from VC (1.81% TN) and the enhanced efficiency of urea-N uptake due to improved soil conditions [47, 62]. The positive correlation between OC and TN (r = 0.920, Fig. 3) confirms the close coupling of carbon and nitrogen cycles in these soils.

4.3.3. Available phosphorus

The increase in available P from 6.25 ppm (control) to 10.37 ppm (3.75 t/ha^{-1} VC + 150 kg/ha^{-1} NPSB) represents a 66% improvement (Table 4). However, even the highest value (10.37 ppm) remained below the optimal level of 15 ppm recommended for Ethiopian soils [10]. This partial improvement reflects the strong P-fixing capacity of acidic Nitisols, where Al^{3+} and Fe^{3+} oxides form insoluble Al-P and Fe-P complexes [48].

The mechanisms by which VC increased P availability are multifaceted. First, the VC itself contributed 67.3 ppm available P (Table 2), providing a direct P source. Second, organic acids (e.g., citric, malic, oxalic acids) released during VC mineralization chelated Al^{3+} and Fe^{3+}, reducing P fixation and releasing previously fixed P into solution [46]. Third, the increase in soil pH (from 5.00 to 5.58) reduced the solubility of Al^{3+} and Fe^{3+}, shifting the equilibrium toward more soluble P forms ($H_2PO_4^-$ and HPO_4^{2-}) [48].

Our findings are consistent with those of Terefe et al. [24], who reported that VC and lime application increased available P from 4.91 to 8.55 ppm. Similarly, Feyanbule et al. [27] found that VC combined with NPSB fertilizer increased available P from 6.25 to 10.37 ppm in finger millet systems. These results collectively indicate that while VC can significantly improve P availability in acidic soils, achieving optimal P levels (15-20 ppm) may require higher VC rates, longer-term application, or additional P inputs.

4.3.4. Available sulfur and boron

The dramatic increases in available S (from 9.32 to 16.57 ppm) and available B (from 0.41 to 1.51 ppm) under combined VC and NPSB application (Table 4) represent improvements of 78% and 268%, respectively. These improvements are particularly significant because S and B deficiencies are widespread in Ethiopian highlands due to decades of DAP and urea use without these nutrients [10, 11].

The increase in available S can be attributed to two sources: (1) direct S input from NPSB fertilizer (6.95% S) and VC (87.3 ppm S), and (2) enhanced S mineralization from soil organic matter due to improved microbial activity [55]. The final S concentration (16.57 ppm) exceeded the critical threshold of 10-20 ppm for low S [10], indicating that the combined treatment successfully alleviated S deficiency.

The increase in available B from 0.41 to 1.51 ppm is particularly noteworthy because B is essential for grain set, pollen tube growth, and seed development [49, 63]. The initial B concentration (0.43 ppm) was below the critical level of 0.5 ppm for Ethiopian soils [10], indicating severe B deficiency. The final B concentration (1.51 ppm) exceeded the optimal range of 0.8-2.0 ppm, demonstrating that the combined VC and NPSB application effectively corrected B deficiency. The positive correlation between available B and grain yield ($r = 0.893$, Fig. 3) confirms the critical role of B in barley productivity.

4.3.5. Cation exchange capacity

The increase in CEC from 14.73 to 33.34 cmol(+) kg^{-1} (a 126% increase) under combined VC and NPSB application (Table 4) is one of the most striking results of this study. This increase is directly attributable to the addition of organic matter from VC, which contributes negatively charged functional groups (carboxyl, phenolic, hydroxyl) that bind exchangeable cations [53].

The final CEC (33.34 cmol(+) kg^{-1}) falls within the "high" category (25-40 cmol(+) kg^{-1}) according to Landon (2014), compared to the initial "low" category (14.97 cmol(+) kg^{-1}). This 126% increase is substantially higher than the 10-30% increases typically reported for organic amendments [22, 59]. The exceptional increase in our study may reflect the combined effects of VC (61.3 cmol(+) kg^{-1}, Table 2) and the NPSB fertilizer, which supplied cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) that occupy exchange sites and maintain high CEC.

The practical implication is that VC application not only adds nutrients but also increases the soil's capacity to retain and slowly release those nutrients over time. This slow-release effect is particularly valuable for smallholder farmers with limited access to fertilizers, as it reduces nutrient losses through leaching and improves nutrient use efficiency [20].

4.4. Effects on Barley Yield and Yield Components

The substantial increases in all measured yield components under combined VC and NPSB application (Table 5) demonstrate the integrated benefits of improved soil properties on crop productivity. Grain yield increased from 0.66 to 5.78 t ha^{-1} (an 876% increase), exceeding the national average yield of 2.5 t ha^{-1} [8] and approaching the experimental potential of 5.2-6.0 t/ha^{-1} for the HB1307 variety [56].

The yield increase can be attributed to the cumulative effects of multiple soil improvements. First, the reduction in BD (from 1.41 to 1.26 g/cm^{-3}) and increase in porosity (from 46.7% to 52.3%) facilitated deeper root penetration and greater access to water and nutrients [43]. Second, the amelioration of soil acidity (pH from 5.00 to 5.58) reduced Al^{3+} toxicity, allowing roots to grow more extensively and absorb nutrients more efficiently [6]. Third, the increases in available N, P, S, and B directly supported plant growth, tillering, spike development, and grain filling [49, 54].

The strong positive correlations between grain yield and key yield components (r = 0.894 for kernels spike^{-1}, r = 0.830 for plant height, r = 0.810 for thousand-grain weight; Fig. 3) confirm that yield gains were driven by improvements in all components, not just one factor. The correlation between grain yield and aboveground biomass (r = 0.983) indicates that increased vegetative growth translated efficiently into grain production, with a harvest index of 40.33% in the optimal treatment (Table 5).

Our grain yield results (5.78 t/ha^{-1}) are comparable to those reported by Terefe et al. [24], who achieved 5.30 t/ha^{-1} with VC (5.31 t/ha^{-1}) and lime (3.24 t/ha^{-1}) in malt barley. Similarly, Ejigu et al. [22] reported maize grain yields of 6.07 t ha^{-1} with compost (10 t/ha^{-1}) and urea/NPSB (100/100 kg/ha^{-1}). Feyanbule et al. [27] achieved finger millet yields of 5.78 t/ha^{-1} with VC (3.75 t/ha^{-1}) and NPSB (100 kg/ha^{-1}), which is identical to our optimal treatment. This consistency across studies and crops suggests that the combination of 3.75 t/ha^{-1} VC and 100 kg/ha^{-1} NPSB may have broad applicability across different cropping systems in Ethiopian highlands.

4.5. Correlation Analysis: Synergistic Relationships

The correlation heatmap (Fig. 3) provides a comprehensive visualization of the relationships among soil properties and agronomic parameters. Several strong correlations merit discussion.

First, the strong positive correlation between grain yield and aboveground biomass (r = 0.983) indicates that yield increases were driven primarily by increased biomass production rather than by changes in harvest index. This is typical for crops grown on severely degraded soils, where initial yield improvements come from overall growth enhancement rather than reallocation of assimilates [20].

Second, the positive correlations between grain yield and soil OC (r = 0.881), TN (r = 0.900), Av. P (r = 0.845), Av. S (r = 0.800), and Av. B (r = 0.893) confirm that improvements in all measured soil properties contributed to yield gains. The particularly strong correlation with Av. B (r = 0.893) highlights the importance of B for barley, which is consistent with the critical role of B in pollen tube growth and grain set [49].

Third, the negative correlation between BD and grain yield (r = -0.650) confirms that soil compaction limits productivity, and that VC-induced reductions in BD improve yield. This is consistent with the findings of Nawaz et al. [43], who reported that soil compaction reduces root penetration, nutrient uptake, and crop yields.

Fourth, the strong positive correlation between OC and CEC (r = 0.950) confirms that organic matter is the primary source of CEC in these soils, which is typical for highly weathered tropical soils where 2:1 clay minerals are less abundant [53]. This correlation suggests that increasing soil OC through VC application will simultaneously increase CEC, creating a positive feedback loop for nutrient retention and availability.

4.6. Economic Feasibility and Practical Implications

The partial budget analysis (Table 6) provides compelling evidence for the economic viability of integrated VC and NPSB application. The optimal treatment (3.75 t ha^{-1} VC + 100 kg ha^{-1} NPSB) yielded a net benefit of 218,335.5 ETB ha^{-1} with an MRR of 681.75%, far exceeding the minimum acceptable threshold of 100% [39]. This high MRR indicates that every 1 ETB invested in inputs returns 6.82 ETB in additional net benefit.

The economic analysis also revealed that the cost of VC (7 ETB kg^{-1}) and NPSB (48 ETB kg^{-1}) is offset by the substantial increase in grain yield (from 0.66 to 5.78 t ha^{-1}). At the farm gate price of 46.5 ETB kg^{-1} for barley grain, the additional 5.12 t ha^{-1} of grain (after 10% adjustment) generates 238,080

ETB ha^{-1} in additional gross benefit, compared to the total variable cost of 35,100 ETB ha^{-1}.

These economic returns are particularly important for smallholder farmers in Ethiopia, who often operate with limited financial resources and high risk aversion. The high MRR (681.75%) provides a strong incentive for adoption, even for farmers with limited capital. Moreover, the VC can be produced on-farm using locally available materials (cow dung, crop residues, green biomass), reducing the cash outlay for inputs [64]. This on-farm production potential makes the technology accessible even to the poorest farmers.

4.7. Comparison with Published Studies and Mechanistic Insights

Our findings align with and extend the growing body of literature on integrated soil fertility management in tropical agroecosystems. A synthesis of recent Studies reveals consistent patterns of soil improvement and yield enhancement with integrated approaches.

Table 7: Comparison of integrated nutrient management studies in Ethiopian highlands

Study	Crop	VC/Compost (t/ha^{-1})	Fertilizer (kg/ ha^{-1})	Yield increase (%)	Key soil improvements
Terefe et al. [24]	Malt barley	5.31 VC	3.24 lime	244%	pH +1.12, OC +66%, AvP +74%
Ejigu et al. [22]	Maize	10 compost	100/100 urea/NPSB	419%	BD -11%, pH +0.2, OC +38%
Feyanbule et al. [27]	Finger millet	3.75 VC	100 NPSB	876%	pH +0.58, OC +25%, AvP +66%
This study	**Barley**	**3.75 VC**	**100 NPSB**	**876%**	**pH +0.58, OC +25%, CEC +126%**

The consistency of yield improvements across these studies (244-876%) demonstrates the robustness of integrated approaches in Ethiopian highlands. However, our study uniquely demonstrates the combined effects of VC with a multi-nutrient (NPSB) fertilizer rather than traditional NP or NPK blends, addressing the specific S and B deficiencies prevalent in Western Ethiopia [10].

The mechanistic framework emerging from these studies (Fig. 5) involves multiple interacting pathways: (1) direct nutrient supply from both VC and mineral fertilizers; (2) pH amelioration through organic matter buffering and Al^{3+} complexation; (3) physical improvements (reduced BD, increased porosity, enhanced aggregation); (4) increased CEC and nutrient retention; (5) reduced P fixation through organic acid chelation; and (6) enhanced biological activity and nutrient mineralization.

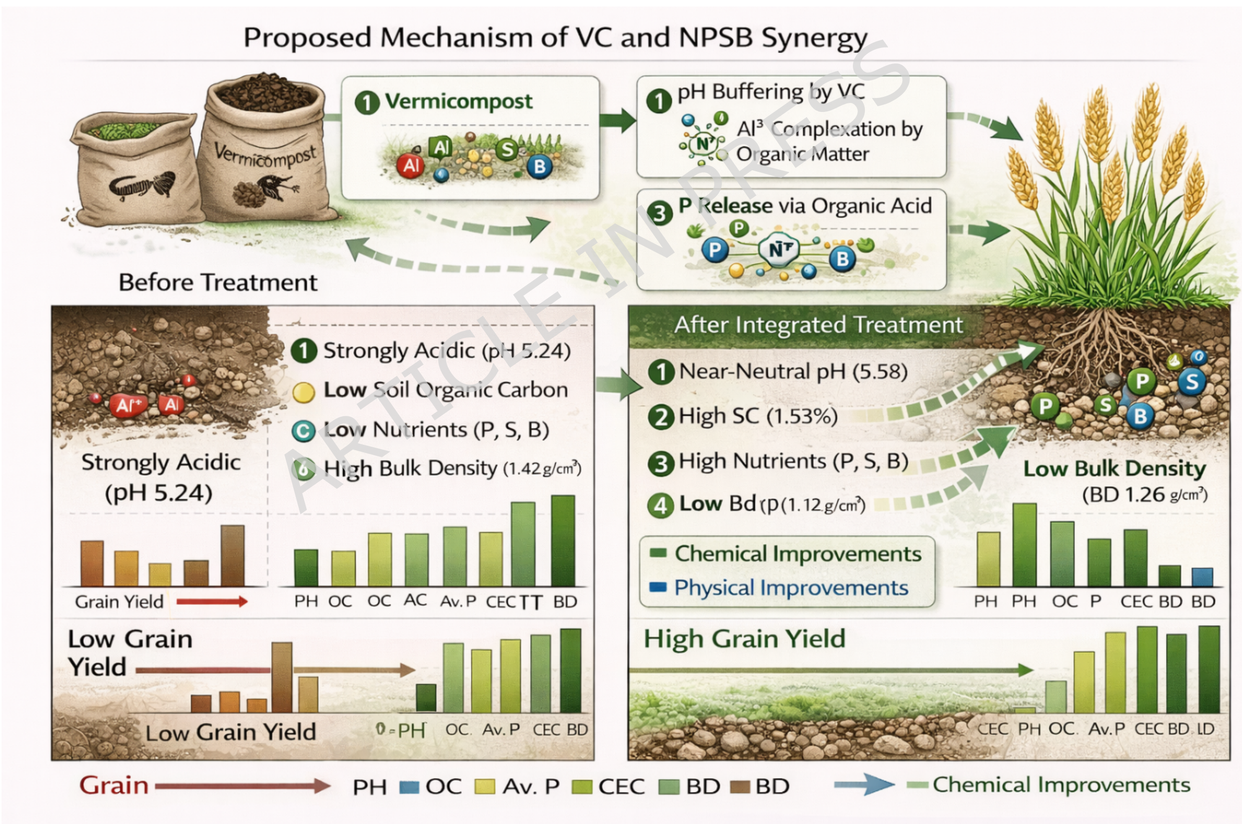

Figure 5: Proposed Mechanism of VC and NPSB Synergy

4.8. Limitations and Future Research Directions

Several limitations of this study should be acknowledged, as they point to important directions for future research. First, the single-season duration of the experiment limits our ability to assess the residual effects of VC and NPSB on soil properties and crop yields over time. Long-term studies (3-5 years) are needed to determine whether the observed improvements are sustained, increase further, or decline with repeated cropping. Such studies would also reveal the optimal frequency of VC application (e.g., annual vs. biennial) for maintaining soil fertility.

Second, our sampling was limited to the topsoil (0-20 cm depth). Deeper soil layers (>20 cm) may respond differently to surface-applied amendments, particularly for mobile nutrients like N and S. Future studies should include subsoil sampling (20-50 cm) to assess nutrient leaching and the depth distribution of organic carbon.

Third, we did not measure soil biological properties (e.g., microbial biomass, enzyme activities, soil respiration, microbial community composition). These indicators are critical for understanding the mechanisms of organic matter decomposition, nutrient mineralization, and soil health [17]. Future studies should incorporate biological measurements to elucidate the microbial mechanisms underlying VC effects.

Fourth, the study was conducted at a single location with Dystric Nitisols. Extrapolation to other soil types (Vertisols, Luvisols, Cambisols, Andosols) or agro-ecological zones (different rainfall regimes, temperatures, altitudes) requires caution. Multi-location trials across Ethiopia's diverse agricultural landscapes are needed to develop region-specific recommendations.

Fifth, the economic analysis used input and output prices from the 2023/2024 season. Price fluctuations (e.g., fertilizer subsidies, market changes) may affect the profitability of the recommended treatment in different years. Sensitivity analyses should be conducted to assess the robustness of economic recommendations under different price scenarios.

Finally, our study used a single barley variety (HB1307). Different varieties may respond differently to integrated nutrient management due to variations in nutrient use efficiency, root architecture, and stress tolerance. Future studies should test multiple varieties to identify genotype-specific recommendations.

4.9. Synthesis and Broader Implications

This study provides robust evidence that integrated application of vermicompost (3.75 t/ha^{-1}) and blended NPSB fertilizer (100 kg/ha^{-1}) can simultaneously address multiple soil fertility constraints in acidic Nitisols of the Ethiopian highlands. The 876% increase in barley grain yield demonstrates the transformative potential of this approach for smallholder farmers who currently achieve yields of only 0.5-1.5 t/ha^{-1}.

From a broader perspective, our findings contribute to the growing recognition that integrated soil fertility management is essential for sustainable intensification in sub-Saharan Africa [20]. The success of this approach depends on the availability of high-quality organic amendments (like VC) and the appropriate mineral fertilizers (like NPSB) that address specific nutrient deficiencies. Policy interventions that support on-farm VC production, improve access to blended fertilizers, and provide extension services on integrated nutrient management could accelerate adoption and improve food security across the region.

Moreover, the carbon sequestration potential of VC application (25% increase in SOC) contributes to climate change mitigation, aligning with the "4 per 1000" initiative that aims to increase global SOC stocks by 0.4% annually [57, 58]. The improved soil physical properties (reduced BD, increased porosity) also enhance climate resilience by improving water infiltration and retention during drought periods.

5. Conclusions

This study provides mechanistic evidence that integrated application of vermicompost (VC) and blended NPSB fertilizer is a highly effective strategy for improving soil physicochemical properties and increasing barley yield in the acidic Nitisols of the Horro District, Western Ethiopia. Our hypothesis that combined VC and NPSB would enhance soil properties more than sole applications was supported: the treatment with 3.75 t/ha^{-1} VC and 100 kg/ha^{-1} NPSB increased soil pH by 0.58 units, OC by 25%, TN by 67%, Av. P by 65%, Av. S by 78%, Av. B by 268%, and CEC by 122%, while reducing BD by 12% compared to the control. Our second hypothesis was also supported: these soil improvements translated into substantial yield gains, with grain yield increasing from 0.66 to 5.78 t/ha^{-1} (an 876% increase). Our third hypothesis was confirmed: the integrated treatment was economically feasible, with a net benefit of 218,335.5 ETB ha^{-1} and an MRR of 681.75%, well above the 100% threshold.

Based on these findings, we recommend that smallholder farmers in the Horro District and similar agro-ecological zones adopt the integrated application of 3.75 t/ha^{-1} VC and 100 kg/ha^{-1} NPSB fertilizer to restore soil fertility, improve barley productivity, and enhance food security. However, given the single-season nature of this study, further research is needed to (1) assess the long-term residual effects of these amendments on soil health and crop yields, (2) evaluate responses in deeper soil layers, (3) incorporate soil biological indicators, (4) test the treatment across diverse soil types and climatic conditions, and (5) investigate the optimal frequency of VC application for sustained benefits.

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References

1. Van Beek, C. L., et al. (2016). Soil nutrient balances under diverse agro-ecological settings in Ethiopia. *Nutrient Cycling in Agroecosystems*, 106(3), 257-274. https://doi.org/10.1007/s10705-016-9803-0
2. Sanchez, P. A. (2002). Soil fertility and hunger in Africa. *Science*, 295(5562), 2019-2020. https://doi.org/10.1126/science.1065256
3. Alam, M. J., Islam, M. S., Mondol, A. T. M. A. I., Naser, H. M., Salahin, N., Alam, M. K., Islam, M. M., Akter, S., & Alam, Z. (2024). Cropping system-based fertilizer strategies for crop productivity and soil health

under minimum tillage in grey terrace soil. *Heliyon*, 10(1), Article e24106. https://doi.org/10.1016/j.heliyon.2024.e24106.

4. Abebe, T. G., et al. (2022). Growing use and impacts of chemical fertilizers and assessing alternative organic fertilizer sources in Ethiopia. *Applied and Environmental Soil Science*, 2022, 4738416. https://doi.org/10.1155/2022/4738416
5. Haileslassie, A., et al. (2005). Assessment of soil nutrient depletion and its spatial variability on smallholders' mixed farming systems in Ethiopia. *Agriculture, Ecosystems & Environment*, 108(1), 1-16. https://doi.org/10.1016/j.agee.2004.12.007
6. Agegnehu, G., et al. (2021). Extent and management of acid soils for sustainable crop production system in the tropical agroecosystems: a review. *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science*, 71(9), 852-869. https://doi.org/10.1080/09064710.2021.1954239
7. Kaso, T., & Guben, G. (2015). Review of barley value chain management in Ethiopia. *Journal of Biology, Agriculture and Healthcare*, 5(10), 84-97.
8. CSA (Central Statistical Agency). (2020). *Agricultural Sample Survey 2019/20: Report on area and production of major crops*. Statistical Bulletin 584. Addis Ababa, Ethiopia.
9. Moges, T., et al. (2018). Effects of lime and phosphorus fertilizer levels on growth and yield components of malt barley (Hordeum distichum L.) in AngolelanaTera District, North Shewa Zone, Ethiopia. *Advances in Plants & Agriculture Research*, 8(6), 582-589. https://doi.org/10.15406/apar.2018.08.00353
10. EthioSIS (Ethiopian Soil Information System). (2014). *Soil Fertility Status and Fertilizer Recommendation Atlas for Tigray Regional State*. Ministry of Agriculture (MoA) and Agricultural Transformation Agency (ATA).
11. Hussien Siraj, T. (2023). Review on Role of Micronutrients, Current Status, and Knowledge Gaps in Ethiopian Agriculture for Ensuring Food Security. *International Journal of Novel Research and Development*, 8(9).

12. Mathewos, M., et al. (2025). The effects of domestic sludge and diammonium phosphate on yield and yield components of haricot bean (Phaseolus vulgaris L.) and soil characteristics. *Discover Sustainability*, 6(1), 89. https://doi.org/10.1007/s43621-025-00997-9

13. Loha, G., Derese, M., & Gifole, G. (2023). Effect of Blended nitrogen, phosphorus, sulfur, boron, and potassium fertilizer rates on growth and yield of maize (Zea mays L.) at Sodo Zuriya district, Southern Ethiopia. *Applied and Environmental Soil Science*, 2023, 4008326. https://doi.org/10.1155/2023/4008326

14. Wedajo, M. A., Kidanu, S., & Reggasa, A. (2023). Effect of Compound (NPSB) Fertilizer Type on Yield and Nutrient use Efficiency of Maize (Zea mays L.) at Beko Village in Yeki District, Southwest Ethiopia. *International Journal on Food, Agriculture and Natural Resources*, 4(2), 40-45. https://doi.org/10.46676/ij-fanres.v4i2.143

15. Liu, E., et al. (2010). Long-term effect of chemical fertilizer, straw, and manure on soil chemical and biological properties in northwest China. *Geoderma*, 158(3-4), 173-180. https://doi.org/10.1016/j.geoderma.2010.04.029

16. Rickson, R. J., et al. (2015). Input constraints to food production: the impact of soil degradation. *Food Security*, 7(2), 351-364. https://doi.org/10.1007/s12571-015-0437-x

17. Sarma, B., et al. (2018). Soil organic carbon dynamics in wheat-Green gram crop rotation amended with vermicompost and biochar in combination with inorganic fertilizers: A comparative study. *Journal of Cleaner Production*, 201, 471-480. https://doi.org/10.1016/j.jclepro.2018.08.019

18. Aksakal, E. L., Sari, S., & Angin, I. (2016). Effects of vermicompost application on soil aggregation and certain physical properties. *Land Degradation & Development*, 27(4), 983-995. https://doi.org/10.1002/ldr.2350

19. Shen, Z., et al. (2022). Effects of vermicompost application on growth and heavy metal uptake of barley grown in mudflat salt-affected soils. *Agronomy*, 12(5), 1007. https://doi.org/10.3390/agronomy12051007
20. Vanlauwe, B., et al. (2010). Integrated soil fertility management: operational definition and consequences for implementation and dissemination. *Outlook on Agriculture*, 39(1), 17-24. https://doi.org/10.5367/000000010791169998
21. Selim, M. (2020). Introduction to the Integrated Nutrient Management Strategies and Their Contribution to Yield and Soil Properties. *International Journal of Agronomy*, 2020, 2821678. https://doi.org/10.1155/2020/2821678
22. Ejigu, W., et al. (2021). Integrated fertilizer application improves soil properties and maize (*Zea mays* L.) yield on Nitisols in Northwestern Ethiopia. *Heliyon*, 7(2), e06074. https://doi.org/10.1016/j.heliyon.2021.e06074
23. Bedada, W., et al. (2014). Long-term addition of compost and NP fertilizer increases crop yield and improves soil quality in experiments on smallholder farms. *Agriculture, Ecosystems & Environment*, 195, 193-201. https://doi.org/10.1016/j.agee.2014.06.017
24. Terefe, Z., et al. (2024). Effects of vermicompost and lime on acidic soil properties and malt barley (Hordeum Distichum L.) productivity in Mecha district, northwest Ethiopia. *PLOS ONE*, 19(12), e0311914. https://doi.org/10.1371/journal.pone.0311914
25. Negash, D. A., et al. (2021). Soil erosion risk assessment for prioritization of sub-watershed: the case of Chogo Watershed, Horo Guduru Wollega, Ethiopia. *Environmental Earth Sciences*, 80(17), 589. https://doi.org/10.1007/s12665-021-09865-5
26. Tesema, T., & Gebissa, B. (2022). Multiple Agricultural Production Efficiency in Horro District of Horro Guduru Wollega Zone, Western Ethiopia. *Journal of Agricultural Extension and Rural Development*, 14(2), 45-58.

27. Feyanbule, M. M., Ashagre, H., & Abraham, T. (2025). Effect of vermicompost and NPSB with urea fertilizer rates on finger millet yield and soil physico-chemical properties at Gobu Sayo district, Ethiopia. *Cogent Food & Agriculture*, 11(1), 2474153. https://doi.org/10.1080/23311932.2025.2474153

28. Tadele, H., et al. (2025). Integrated nutrient management for maize phenology and growth performance: Biochar, vermicompost, and N-P nutrients in northwestern Ethiopia. *Agrosystems, Geosciences & Environment*, 8(3), e70158. https://doi.org/10.1002/agg2.70158

29. Dinssa, B., & Elias, E. (2021). Characterization and classification of soils of Bako Tibe district, West Shewa, Ethiopia. *Heliyon*, 7(11), e08289. https://doi.org/10.1016/j.heliyon.2021.e08289

30. Bouyoucos, G. J. (1962). Hydrometer method improved for making particle size analyses of soils. *Agronomy Journal*, 54(5), 464-465. https://doi.org/10.2134/agronj1962.00021962005400050028x

31. Van Reeuwijk, L. P. (2002). *Procedures for soil analysis* (6th ed.). International Soil Reference and Information Centre (ISRIC), Wageningen, Netherlands.

32. Bremner, J. M., & Mulvaney, C. S. (1982). Nitrogen—Total. In A. L. Page, et al. (Eds.), *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties* (2nd ed., pp. 595-624). American Society of Agronomy. https://doi.org/10.2134/agronmonogr9.2.2ed.c31

33. Walkley, A., & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science*, 37(1), 29-38. https://doi.org/10.1097/00010694-193401000-00003

34. Bray, R. H., & Kurtz, L. T. (1945). Determination of total, organic, and available forms of phosphorus in soils. *Soil Science*, 59(1), 39-46. https://doi.org/10.1097/00010694-194501000-00006

35. Wall, L. L., Gehrke, C. W., & Suzuki, J. (1980). An automated turbidimetric method for total sulfur in plant tissue and sulfate sulfur in

soils. *Communications in Soil Science and Plant Analysis*, 11(11), 1087-1103. https://doi.org/10.1080/00103628009367102
36. Bingham, F. T. (1982). Boron. In A. L. Page, et al. (Eds.), *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties* (2nd ed., pp. 431-447). American Society of Agronomy. https://doi.org/10.2134/agronmonogr9.2.2ed.c20
37. Pratt, P.F. (1965). Potassium. In Methods of Soil Analysis, A.G. Norman (Ed.). https://doi.org/10.2134/agronmonogr9.2.c20.
38. Blake, G. R., & Hartge, K. H. (1986). Bulk Density. In A. Klute (Ed.), *Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods* (2nd ed., pp. 363-375). American Society of Agronomy. https://doi.org/10.2136/sssabookser5.1.2ed.c13
39. CIMMYT (International Maize and Wheat Improvement Center). (1988). *From agronomic data to farmer recommendations: An economics training manual* (Rev. ed.). Mexico, D.F.
40. VSN International. (2014). *GenStat for Windows* (15th Edition). VSN International, Hemel Hempstead, UK.
41. Grosbellet, C., et al. (2011). Improvement of soil structure formation by degradation of coarse organic matter. *Geoderma*, 162(1-2), 27-38. https://doi.org/10.1016/j.geoderma.2011.01.003
42. Haque, A. N. A., et al. (2021). Assessing the increase in soil moisture storage capacity and nutrient enhancement of different organic amendments in paddy soil. *Agriculture*, 11(1), 44. https://doi.org/10.3390/agriculture11010044
43. Nawaz, M. F., Bourrie, G., & Trolard, F. (2013). Soil compaction impact and modelling. A review. *Agronomy for Sustainable Development*, 33(2), 291-309. https://doi.org/10.1007/s13593-011-0071-8
44. Aipa, J., & Michael, P. S. (2019). Different land use systems improve soil fertility status of sandy soil and increase the yield of rice under rain-fed wet lowland tropical climatic conditions in Papua New Guinea.

International Journal of Agricultural and Environmental Research, 5, 19-27.

45. Dhaliwal, S. S., et al. (2019). Effect of manures and fertilizers on soil physical properties, build-up of macro and micronutrients and uptake in soil under different cropping systems: a review. *Journal of Plant Nutrition*, 42(20), 2873-2900. https://doi.org/10.1080/01904167.2019.1659337
46. Opala, P. A., Okaleb, J. R., & Othieno, C. O. (2012). Effects of Organic and Inorganic Materials on Soil Acidity and Phosphorus Availability in a Soil Incubation Study. *ISRN Agronomy*, 2012, 597216. https://doi.org/10.5402/2012/597216
47. Mi, W., et al. (2016). Changes in soil organic carbon fractions under integrated management systems in a low-productivity paddy soil given different organic amendments and chemical fertilizers. *Soil and Tillage Research*, 163, 64-70. https://doi.org/10.1016/j.still.2016.05.009
48. Jindo, K., Audette, Y., Olivares, F.L. et al. (2023). Biotic and abiotic effects of soil organic matter on the phytoavailable phosphorus in soils: a review. *Chem. Biol. Technol. Agric*. 10, 29 (2023). https://doi.org/10.1186/s40538-023-00401-y.
49. Shireen, F., et al. (2018). Boron: functions and approaches to enhance its availability in plants for sustainable agriculture. *International Journal of Molecular Sciences*, 19(7), 1856. https://doi.org/10.3390/ijms19071856
50. Hamadani, H. et al. (2021). Traditional Farming Practices and Its Consequences. In: Dar, G.H., Bhat, R.A., Mehmood, M.A., Hakeem, K.R. (eds) Microbiota and Biofertilizers, Vol 2. Springer, Cham. https://doi.org/10.1007/978-3-030-61010-4_6.
51. IUSS Working Group WRB. (2022). World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps (4thed.). International Union of Soil Sciences (IUSS), Vienna, Austria.

52. Jiménez-Prieto, B., García-Palacios, P., Lorenzo-Rodríguez, C. et al. (2026). Consistent topsoil carbon density and driving factors in urban greenspaces and natural ecosystems. *Plant Soil*. https://doi.org/10.1007/s11104-026-08484-w.

53. Ramos, F. T., Dores, E. F. C., Weber, O. L. D. S., Beber, D. C., Campelo, J. H., Jr, & Maia, J. C. S. (2018). Soil organic matter doubles the cation exchange capacity of tropical soil under no-till farming in Brazil. *Journal of the science of food and agriculture*, 98(9), 3595–3602. https://doi.org/10.1002/jsfa.8881.

54. Jalata, A., Delesa, D., Roro, G., Amsalu, A., Dabalo, H., Adugna, A., Bebayehu, A., Fayera, F., Woticha, W., & Tufa, A. (2022). Effect of blended NPSB and nitrogen application rates on growth, yield, and yield components of bread wheat (*Triticum aestivum* L.) at Gitilo Dale research site of Wallaga University, Western Ethiopia. *Advances in Agriculture*, *2022*, 1706039. https://doi.org/10.1155/2022/1706039.

55. Bebayehu, A., Fayera, F., Irge, W., Alemayehu, A., Woticha, T., Abdela, A., Dabalo, H., & Adugna, A. (2023). Influences of NPSB and vermicompost application rates on yields of tomato (*Lycopersicon esculentum* Mill) at Jimma Ganati research site of Wallaga University, Western Ethiopia. *Advances in Agriculture*, *2023*, 4599133. https://doi.org/10.1155/2023/4599133.

56. Bekele, B., & Lakew, B. (2008). Registration of Food Barley (*Hordeum vulgare* L.) Variety HB 1307 for Mid and High Altitude Areas of Ethiopia. East African Journal of Sciences, 2(2). https://doi.org/10.4314/eajsci.v2i2.40383.

57. Vambe, M., Coopoosamy, R. M., Arthur, G., & Naidoo, K. (2023). Potential role of vermicompost and its extracts in alleviating climatic impacts on crop production. *Journal of Agriculture and Food Research*, *12*, 100585. https://doi.org/10.1016/j.jafr.2023.100585.

58. Chowdhury, R., Paul, S., Goswami, L., Bhattacharya, S.S. (2024). The Role of Waste Vermicompost on Soil Organic C Sequestration in Arable

Lands: Some Critical Arguments. In: Bordoloi, N., Bauddh, K., Baruah, K. (eds) Agricultural Greenhouse Gas Emissions: Problems and Solutions. Springer, Singapore. https://doi.org/10.1007/978-981-97-7554-5_7.

59. Azarmi, R., Ziveh, P. S., & Satari, M. R. (2008). Effect of vermicompost on growth, yield and nutrition status of tomato (*Lycopersicum esculentum* M). *Pakistan journal of biological sciences : PJBS*, *11*(14), 1797–1802. https://doi.org/10.3923/pjbs.2008.1797.1802.

60. Custos, J.-M., Moyne, C., & Sterckeman, T. (2020). How root nutrient uptake affects rhizosphere pH: A modelling study. *Geoderma*, *369*, 114314. https://doi.org/10.1016/j.geoderma.2020.114314.

61. Li, K.-W., Lu, H.-L., Nkoh, J. N., Hong, Z.-N., & Xu, R.-K. (2022). Aluminum mobilization as influenced by soil organic matter during soil and mineral acidification: A constant pH study. Geoderma, 418, Article 115853. https://doi.org/10.1016/j.geoderma.2022.115853.

62. Ali A, Jabeen N, Farruhbek R, Chachar Z, Laghari AA, Chachar S, Ahmed N, Ahmed S and Yang Z (2025) Enhancing nitrogen use efficiency in agriculture by integrating agronomic practices and genetic advances. Front. Plant Sci. 16:1543714. https://doi.10.3389/fpls.2025.1543714.

63. Aasim, M., Akgür, Ö., & Yıldırım, B. (2022). An overview on boron and pollen germination, tube growth and development under in vitro and in vivo conditions. In T. Aftab, M. Landi, I. E. Papadakis, F. Araniti, & P. H. Brown (Eds.), Boron in plants and agriculture (pp. 293–310). Academic Press. https://doi.org/10.1016/B978-0-323-90857-3.00014-X.

64. Zerssa, G., Feyssa, D., Kim, D.-G., & Eichler-Löbermann, B. (2021). Challenges of Smallholder Farming in Ethiopia and Opportunities by Adopting Climate-Smart Agriculture. Agriculture, 11(3), 192. https://doi.org/10.3390/agriculture11030192.