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Integrated Vermicompost and Inorganic Fertilizer Application Improves Soil Physicochemical Properties and Bread Wheat (*Triticum aestivum* L.) Productivity on Nitisols of Northwestern Ethiopia

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Abstract

Declining soil fertility is a major constraint to sustainable wheat production in Ethiopian highlands, where nutrient depletion and soil acidity limit crop productivity. Therefore, this study was designed to evaluate the effects of integrated application of vermicompost (VC) and nitrogen-phosphorus (NP) fertilizers on soil physicochemical properties and bread wheat productivity on Nitisols in the Yilmana Densa district, Northwestern Ethiopia, during the 2025 main cropping season. A randomized complete block design (RCBD) with three replications was employed using a 4 × 4 factorial arrangement consisting of four VC rates (0, 3, 6, and 9 t/ha) and four NP fertilizer levels (0/0, 46/46, 92/69, and 138N/92 P₂O₅ kg/ha). Vermicompost significantly increased soil pH, organic carbon, total nitrogen, available phosphorus, cation exchange capacity, and total porosity, while reducing bulk density. The combined application of 9 t/ha VC with 138N/92 P₂O₅ kg/ha produced the highest grain yield (5.0 and 5.6 t/ha), biomass (11.0 and 12.1 t/ha), and straw yield (6.0 and 6.5 t/ha) at the two experimental sites, respectively. Partial budget analysis based on pooled yield data revealed that this treatment generated the highest net benefit (324,853.3 Ethiopian Birr/ha) with a marginal rate of return (429%). The results demonstrate that integrating VC and NP fertilizers enhances soil and bread wheat productivity. Therefore, the combined application of 9 t/ha VC and 138N plus 92 P₂O₅ kg/ha is recommended for bread wheat production in the study area and similar agro-ecological conditions.

Keywords: Bread wheat, integrated soil fertility management, Vermicompost, Nitrogen, Phosphorus, Soil physicochemical properties

Introduction

Soil fertility is a key determinant of crop productivity, food security, and sustainable agricultural development, particularly in developing countries where agriculture remains the dominant livelihood sources [1, 2]. In Ethiopia, agriculture contributes substantially to the national economy and supports the livelihoods of the majority (> 80%) of the population [3, 4]. However agricultural productivity is increasingly constrained by declining soil fertility, which has emerged as one of the most critical challenges to sustainable crop production in the country [5, 6].

Soil degradation, characterized by nutrient depletion, organic matter decline, erosion, and soil acidification, is widespread across Ethiopia and is particularly severe in the highland agro ecosystems [7]. Nutrient losing rates in the country are among the highest in sub-Saharan Africa, with annual losses estimated at approximately 122kg N/ha, 13kgP/ha, and 82kg K/ha [8]. As a result many agricultural soils exhibit low organic matter content, nutrient deficiencies, reduced biological activity, and poor physical conditions, ultimately limiting crop productivity [9-11].

In addition to nutrient depletion, soil acidity affects approximately 40-43% of Ethiopia's cultivated lands, particularly in humid and sub-humid highlands [12]. The problem is especially evident in Nitisol-dominated area of Northwestern Ethiopia, where prolonged cultivation has reduced soil organic matter, available phosphorus, and nitrogen levels, leading to poor soil structure, diminished water-holding capacity, and restricted nutrient availability [13, 14]. These constraints highlight the need for sustainable soil fertility management strategies that simultaneously improve soil quality and crop productivity.

To address declining soil fertility, mineral fertilizers have been widely promoted and adopted in Ethiopia. The use of nitrogen and phosphorus fertilizers has contributed substantially to increased crop yields; however, the sole application of inorganic fertilizers often fails to maintain long-term soil health because it does not adequately replenish soil organic matter or improve soil physical and biological properties [6, 15].

Furthermore, the effectiveness of mineral fertilizers is frequently constrained by high costs, limited accessibility, and low nutrient use efficiency under smallholder farming conditions [16, 17].

Integrated soil fertility management (ISFM) which combines organic and inorganic nutrient sources, has therefore been increasingly advocated as a sustainable approach to improve soil fertility and crop productivity [18, 19]. The integration of organic amendments like vermicompost (VC) with mineral fertilizers enhances nutrient availability, improves soil structure, stimulates microbial activity, increase nutrient use efficiencies, and reduces nutrient losses [9, 18-20]. Several studies conducted in Ethiopia have demonstrated that integrated nutrient management improve both soil properties and crop yields more effectively than the sole application of either organic or inorganic nutrient sources [21-25].

Bread wheat (*Triticum aestivum* L.) is one of the most important cereal crops in Ethiopia, serving as a major source of food, income, and livelihood for millions of smallholder farmers [3, 26]. It ranks among the leading cereal crops in terms of area cultivated and production and plays a crucial role in national food security [3, 4, 26]. Despite its importance, the national average is substantially lower than yields achieved under improved management practices, largely due to soil fertility decline nutrient depletion, inappropriate fertilizer management, and other biophysical and socioeconomic constraints [3, 7, 27].

Although, integrated nutrient management has been widely recognized as a promising strategy for improving wheat productivity and soil health [19, 24], information on the optimal combination of VC and inorganic nitrogen (N) and phosphorus (P) fertilizers remains limited in the Nitisol-dominated highlands of Northwestern Ethiopia. Therefore, this study was conducted to evaluate the effects of integrated application of vermicompost and inorganic NP fertilizers on soil physicochemical properties and bread wheat productivity in the Yilmana Densa district of Northwestern Ethiopia. The study further aimed to identify an agronomically effective and economically viable nutrient

management option capable of enhancing wheat yield while improving soil fertility under the prevailing agro ecological conditions of the study area.

2. Materials and Methods

2.1. Description of the Study Area

The field experiment was conducted during the 2025 main cropping season on the Nitisols in the Yilmana Densa district, Amhara Regional State, Northwestern Ethiopia. The study was undertaken at two locations: Adet Hana *Kebele* and Mossebo *Kebele* on Farmer's field. The district is located between 11°06'–11°24' N latitude and 37°16'–37°43' E longitude (Fig.1), with elevations ranging from 1800 to 3000 meter above sea level [28]. The area is predominantly characterized by midland agro-ecology (72.5%), followed by highland (21.5%), and low land (6.25%) zones [28]. The district experiences a unimodal rainfall pattern extending from May to October (Fig. 2). Based on an 11-year climate data recorded, the mean annual rainfall is 1308 mm[29], while the average minimum and maximum temperature are 11°C and 27°C, respectively.

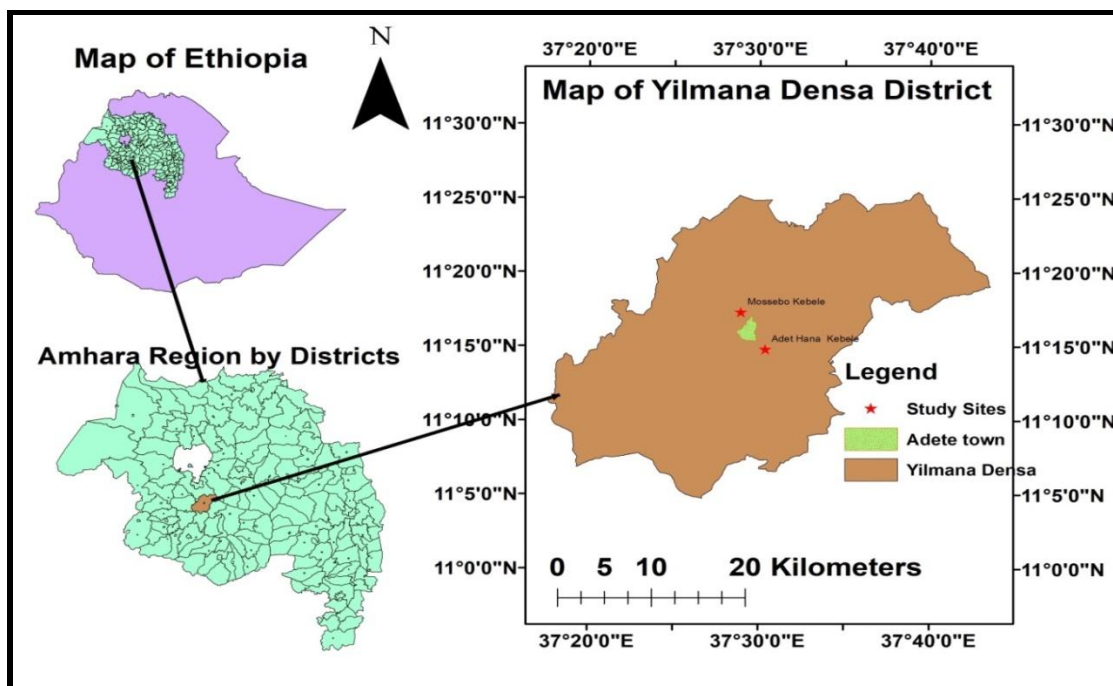


Fig.1 Map of the study area

During the experimental season (2025), total rainfall reached 1437mm, with minimum and maximum temperature of 10°C and 29°C, respectively (**Fig. 2**). Nitisols are the dominant soil type covering about 65% of the district, followed by Vertisols (20%) and Cambisols (15%) [28]. Rain-fed mixed crop–livestock farming is the major agricultural production system, with tef (*Eragrostis tef*) (73%), maize (*Zea mays* L.) (87%), wheat (*Triticum aestivum*) (35 %), potato (*Solanum tuberosum*) (25%), barely (*Hordeum vulgare*) (37%), others cover 10% [28, 30].

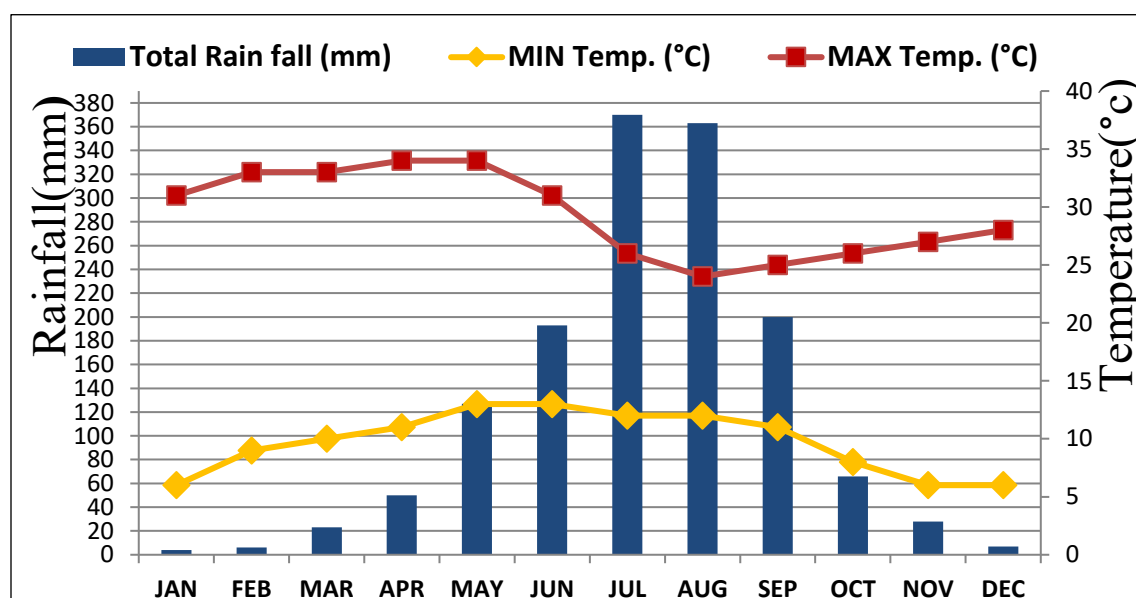


Fig. 2 Weather data during experimental year (2025) of the study area

2.2. Experimental Design and Treatment Set up

The experiment was conducted during the 2025 rainy season using the bread wheat variety (*Triticum aestivum* L) 'kekeba', which is well adapted in the study area and used as a test crop at seeding rate of 150 kg/ha [31]. A randomized complete block design (RCBD) with three replications was employed in a 4 × 4 factorial arrangement consisting of four vermicompost rates 0,3,6,and 9 t/ha and four NP fertilizer levels (0/0,46/46,92/69, and 138/92 kg N/P₂O₅). The treatment details are shown in Table 1. Vermicompost (VC) was incorporated by broadcast into the plots two weeks before planting. Urea (46 N-0 P-0 K) as source of nitrogen and triple super-phosphate (TSP) (46 P₂O₅) as source of Phosphorus fertilizers were used in the experiment. Phosphorus

fertilizer (TSP) was applied entirely at planting and nitrogen was applied as urea in three equal splits: 1/3 at planting, 1/3 at 35 days after germination, and 1/3 at the booting/flowering stage.

Table 1 Treatment details

Treatments	Treatment combinations	Symbol	Remark
T1	Control(0)	0VC+0/0NP	absolute control
T2	0 VC t/ha +46N kg/ha+46P ₂ O ₅ kg/ ha	0VC+46/46NP	
T3	0 VC t/ha +92Nkg/ha+69 P ₂ O ₅ kg /ha	0VC+92/69NP	
T4	0 VC t/ha+138Nkg/ha+92P ₂ O ₅ kg/ha	0VC+138/92NP	RNP fertilizer
T5	3VC t/ha+ 0N kg/ha+0 P ₂ O ₅ kg/ha	3VC+0/0NP	
T6	3VCt/ha+46Nkg/ha +46 P ₂ O ₅ kg/ha	3VC+46/46NP	
T7	3VCt/ha+92Nkg/ha+69P ₂ O ₅ kg/ha	3VC+92/69NP	
T8	3VCt/ha+138Nkg/ha+92 P ₂ O ₅ kg/ha	3VC+138/92NP	
T9	6VC t/ha+ 0N kg/ha+0 P ₂ O ₅ kg/ha	6VC+0/0NP	
T10	6VCt/ha+46Nkg/ha +46 P ₂ O ₅ kg/ha	6VC+46/46NP	
T11	6VCt/ha+92N kg/ha+69P ₂ O ₅ kg/ha	6VC+92/69NP	
T12	6VC t/ha +138Nkg/ha+92P ₂ O ₅ kg/ ha	6VC+138/92NP	
T13	9VC t/ha + 0N kg/ha +0P ₂ O ₅ kg/ ha	9VC+0/0NP	
T14	9VC t/ha +46N kg/ha+46P ₂ O ₅ kg /ha	9VC+46/46NP	
T15	9VCt/ha +92N kg/ha+69 P ₂ O ₅ kg /ha	9VC+92/69NP	
T16	9VCt/ha+138Nkg/ha+92 P ₂ O ₅ kg/ ha	9VC+138/92NP	

Where, VC tha⁻¹ = Vermicompost (VC) in ton per hectare, T=Treatment

N kgha⁻¹ = Nitrogen fertilizer (N) in kilogram per hectare from of urea

P₂O₅ kg ha⁻¹= Phosphorus fertilizer (P) in kilogram per hectare in from of TSP

NP= Nitrogen (N) and phosphorus P in form of P₂O₅) in kg per hectare,
RNP=recommended NP fertilizers.

2.3. Soil Sampling, Preparation and Analysis

All soil samples used in this experiment were collected in accordance with the national standard procedures outlined in the manual by [32]. Soil samples were collected before planting and after harvesting at each study site using a soil auger at a depth of 0-20 cm

with “X” sampling methods to assess the status of soil fertility before planting and the changes in soil properties after harvesting. Then the samples were air-dried, ground by mortar and pestle, and sieved through a two (2) mm sieve for the analysis of soil texture, Cation exchange capacity (CEC), soil reaction (pH), and available phosphorus (AvP). For the determination of the organic carbon (OC) and total nitrogen (TN), a 0.5 mm sieve was used. For bulk density analysis, soil core samples were collected using a core sampler at both experimental sites.

The particle size distribution of the soil was determined using the hydrometer method as described by Bouyoucos [33]. Soil bulk density (BD) was measured using a core sampling technique following the procedure of Blake and Hartge [34]. Soil pH was measured in a 1:2.5 soil-to-water suspension method using a digital PHS-3E pH meter, in accordance with Van Reeuwijk [35]. The TN was analyzed using the micro-Kjeldahl method [36]. Soil OC was determined through the wet digestion method as outlined by [36]. Soil Ava.P was extracted using sodium bicarbonate (NaHCO_3) following the Bray II method [37]. Soil CEC was determined using the ammonium acetate extraction method following the procedure described by Black [38]. The vermicompost (VC) used in the experiment was analyzed using the same analytical methods as those applied to the soil. All soil and VC properties described in this document were analyzed at Adet Agricultural Research Center Soil Laboratory following the procedures in the compiled manual of Sahlemedhin and Taye [39].

2.4. Agronomic Data Collection

All agronomic data used in this experiment were collected following the procedures described by [32]. At physiological maturity, plant height, spike length, and kernels per spike were recorded using ten (10) randomly selected plants from each harvestable plot. The harvested wheat of each plot was first air-dried for threshing. Subsequently, the total above-ground biomass was recorded before threshing. Then, the grain yield and grain moisture were measured simultaneously. Finally, the grain yield was adjusted to the standard moisture content of 12.5% for bread wheat using the following formula [32]:

$$\text{Adjusted yield} = \text{Actual Yield} \times \frac{(100 - M)}{100 - 12.5\%}$$

Where, M is the measured actual moisture content (%) of bread wheat grain of each plot.

2.5. Data Analysis

All collected data were subjected to analysis of variance (ANOVA) with the general linear model (GLM) procedure by using the R statistical software program version 4.3.3. When ANOVA indicated significant treatment effects, treatment means comparisons were performed using Tukey's Honest Significant Difference (HSD) test at the 5% significant level following the procedure of Gomez and Gomez [40].

2.6. Economic Analysis

A partial budget analysis was performed according to the CIMMYT methodology[41] to determine the costs and benefits of the treatments. The local cost of nitrogen from urea was 149.3 Ethiopian Birr (ETB)/kg, while P₂O₅ from DAP was 64.5 ETB/kg. Additionally, vermicompost (VC) was used at a rate of two ETB/ kg to estimate the total variable costs. The gross field costs and benefits were estimated by multiplying grain and straw yields by their present local costs of 70 ETB/ kg and 125 ETB/q, respectively. The net benefit (NB) was estimated by subtracting total variable costs from the gross benefit (GB). Then, the treatments were arranged in increasing order by their total variable costs (TVC). Then, the marginal rate of return (MRR) was calculated by excluding the dominated treatments following the equation stated by CIMMYT [41]:

$$\text{MRR (\%)} = \frac{\text{NB2} - \text{NB1}}{\text{TV2} - \text{TV1}} \times 100$$

Where, NB1 = Net benefit of the lowest-cost treatment, NB2 = Net benefit of the higher-cost treatment, TV1 = Total variable cost of the lower-cost treatment, TV2 = Total variable cost of the higher-cost treatment

3. Result and Discussion

3.1. Before Planting Soil Physicochemical Properties of the Experimental Locations/Sites

The initial physicochemical soil properties of the experimental sites are presented in table 2. The soils exhibited strongly to very strong acidic reactions (pH 4.9-5.3), indicating potential constraints to nutrient availability and the possible need for acidity management to optimize bread wheat production [42]. Total nitrogen (TN) level were within the medium range, whereas available phosphorus (Ava.P) was low, suggesting a likelihood of phosphorus limitation (Table 2). Soil organic carbon (OC) content was also low, reflecting limited organic matter status for both experimental locations/Sites. In contrast the soils had relatively high cation exchange capacity (CEC) (27.1-28.5 cmol (+)/kg of soil), indicating good nutrient retention capacity. Bulk Density (BD) (1.3-1.35 g/cm³), porosity (49.1-50.8%), and C: N ratio was within ranges considered favorable for cultivated soils [43-46].

Table 2 Before-planting soil properties of the experimental locations/sites

Pre-Planting Soil Properties						
Parameters	Site 1	Ratings	References	Site 2	Ratings	References
pH	4.9	very strongly acidic	[44]	5.30	strong	[44]
OC (%)	1.25	low	[44]	1.56	low	[44]
TN (%)	0.13	medium	[44]	0.14	medium	[44]
Ava.P(ppm)	6.7	low	[47]	7.6	low	[47]
CEC(cmol+)/kg)	28.5	high	[44]	27.1	high	[44]
BD(g/cm ³)	1.35	moderate	[42]	1.30	low	[42]
C:N ratio	10:1	medium	[9]	11:1	medium	[9]
Porosity (%)	49.1	high	[42]	50.8	high	[42]
Clay (%)	60			58		
Silt (%)	24			27		
Sand (%)	16			15		
Textual class	clay		[46]	clay		[46]
Soil color	reddish	reddish	[48]	reddish	reddish	[48]

3.2. Vermicompost Characteristics Used in the Experiment

The vermicompost (VC) used in the experiment was analyzed in the laboratory, and the result showed that a high quality indicators in terms of maturity and chemical properties

(Table 3). Generally, the vermicompost used in our experiment showed good nutrient content, high CEC, balanced C: N ratio, and neutral pH, making it an effective amendment and nutrient source when integrated with NP fertilizers [20, 23].

Table 3 Characteristics and nutrient content of VC used in the experiment

Vermicompost (VC) Characteristics						
Parameters	pH	OC (%)	TN (%)	Avai.P(ppm)	CEC(cmol+)/kg)	C:N ratio
Values	7.5	12.88	1.27	266.17	58.42	10:1
Ratings	Slightly alkaline	high	high	medium	Very high	medium
References	[44]	[44]	[44]	[17]	[44]	[9]

3.3. Soil Response to Integrated Vermicompost (VC) and Nitrogen-Phosphorus (NP) Fertilizer Application

3.3.1. Soil Reaction (pH)

The analysis of variance showed that VC application significantly increased soil pH at both experimental sites at $p \leq 0.01$ (Table 4). Soil pH rose with increasing VC rates at both locations (Fig. 3a). The control treatment (0 t VC/ha) showed the lowest pH values of 4.98 at Site 1 and 5.24 at Site 2. The highest pH value was observed from the treatment that received 9 t/ha VC, reaching 5.35 at Site 1 and 5.39 at Site 2 (Fig. 3a). Compared to the control treatment, 9 t/ha VC increased the pH value by 7.43% at Site 1 and 2.87% at Site 2. This improvement could be due to the liming effect of VC, which supplies basic cations (Ca^{2+} , Mg^{2+} , and K^{+}) that neutralize soil acidity [20]. Additionally, the increase in pH may result from the buffering capacity of organic matter and the replacement of hydrogen (H^{+}) and aluminum (Al^{3+}) ions by basic cations. It can also be attributed to the decarboxylation of organic anions during decomposition, which consumes protons and reduces soil acidity. The non-significant effect of NP fertilizer on soil pH (Table 4) may suggest that the application of inorganic fertilizer did not improve soil pH values.

Table 4 ANOVA showing the effect of integrated VC and NP fertilizer application on some soil physicochemical properties

Source of Variation	Soil Reaction (pH)		Soil Total Nitrogen (TN)		Soil Available Phosphorus (Ava.P)			
	Site 1	Site 2	Site 1	Site 2	Site 1		Site 2	
VC	0.0005	0.0006	<0.0001	<0.0001	0.0067		0.0001	
NP	ns	ns	ns	ns	0.0003		0.0002	
VC x NP	ns	ns	ns	ns	ns		ns	
Site	<0.0001		<0.0001		<0.0001			
CV (%)	1.6	1.2	8	4.7	10.6		13.4	
Sources of Variation	Soil Organic Carbon (OC)		Soil Cation Exchange Capacity (CEC)		Soil Bulk Density (BD)		Soil total porosity	
							Site 1	Site 2
VC	<0.0001	<0.0001	0.0008	<0.0001	<0.0001	<0.0001	0.0421	0.0434
NP	ns	ns	ns	ns	ns	ns	ns	ns
VC x NP	ns	ns	ns	ns	ns	ns	ns	ns
Site	<0.0001		<0.0001		<0.0001		0.0002	
CV (%)	7.2	3.4	5.5	5.4	2.7	2.6	2.7	3.4

Where, VC=vermicompost rate (t/ha), NP=nitrogen and phosphorus fertilizer rate(kg/ha) and P in the form of P₂O₅, Soil Reaction measured in pH, TN in %, Ava.P in ppm, OC in %, ECE in cmol (+)/kg soil, BD in g/cm³, LSD=least significant differences= non-significant at p > 0.05, * =significant at P ≤ 0.05, **=significant at P ≤ 0.01,CV=coefficient of variation.

Inorganic fertilizers typically have a neutral effect or may cause acidification through nitrification of ammonium-based nitrogen sources [44, 49]. The absence of a significant interaction effect of VC and NP fertilizers on soil pH (Table 4) at both study sites may indicate that VC's pH-enhancing effect operates independently of inorganic fertilization. This finding is consistent with Abebe et al.[50], who also observed an independent effect of VC on Soil pH when combining VC with inorganic fertilizers. Gebrekidan et al. [51] also found that VC application significantly increased soil pH in acidic Nitisols.

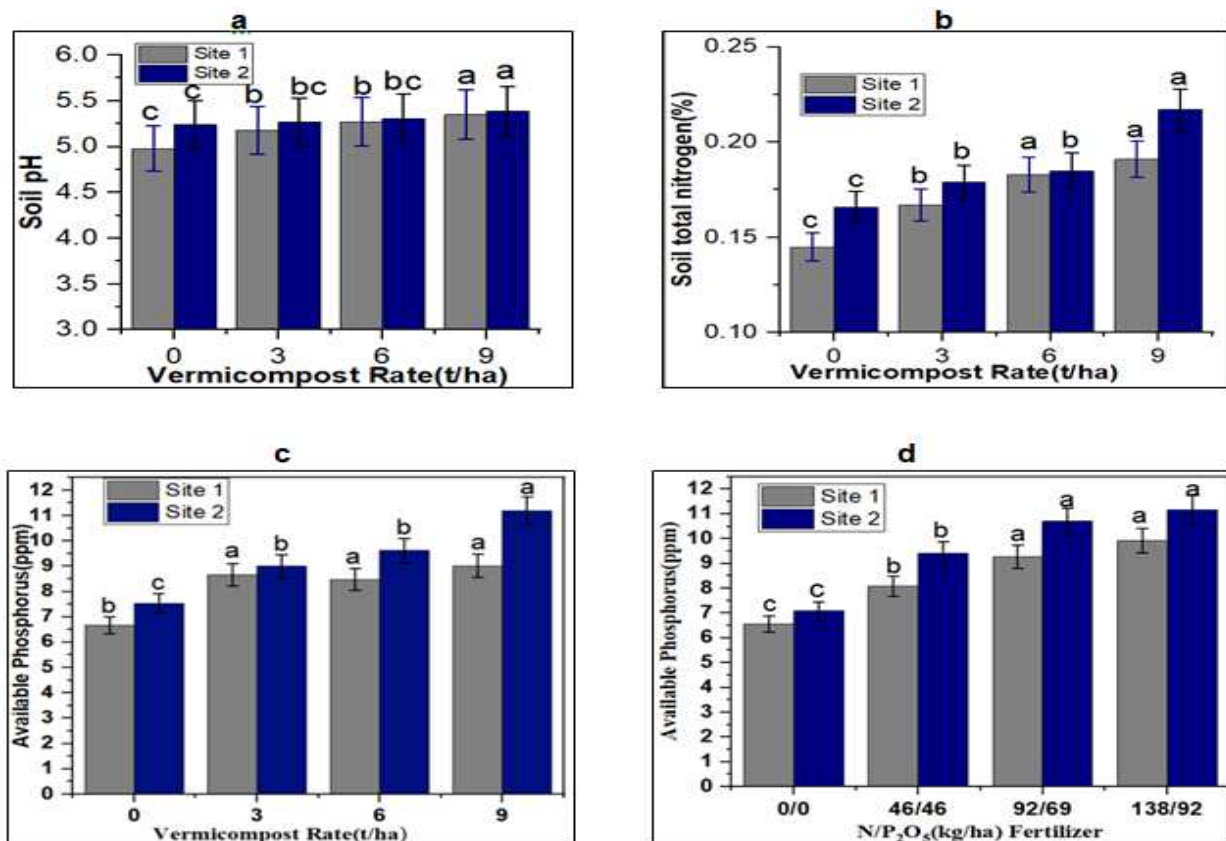
3.3.2. Soil Total Nitrogen (TN)

Soil total nitrogen (TN) was significantly ($p \leq 0.01$) influenced by VC application at both experimental sites. In contrast, NP fertilizer did not show a significant effect on TN at either experimental site (Table 4). Likewise, the interaction of VC and NP was not significant, which indicates that the observed TN improvement was mainly attributed to

VC application and inorganic fertilizers mainly supply readily available nitrogen with limited contribution to stable soil nitrogen pools [52]. Total nitrogen increased significantly with increasing VC rates at both experimental locations, indicating the potential of VC to improve soil TN status through the addition of organic nitrogen and enhanced microbial-mediated mineralization [23]. The lowest TN values were recorded in the control treatment (0.145% at Site 1 and 0.166% at Site 2), while the highest values were obtained from treatments that received 9 t/ha VC alone (0.191% at Site 1 and 0.217% at Site 2), presented on (Fig. 3b). This represents an increase of 31.7% and 30.7% over the control at Site 1 and Site 2, respectively. These findings agree with previous studies reporting improved soil TN following VC application through enhanced organic matter inputs and nutrient cycling [23, 53-56].

3.3.3. Soil Available Phosphorus (Ava.P)

Soil available phosphorus (Ava.P) was significantly ($P \leq 0.01$) increased by both VC and NP fertilizer at both study sites (Table 4). The higher Ava.P values under VC application were recorded at 9 t/ha VC (9.02ppm at Site 1 and 11.19 ppm at Site 2), representing increase of 35.5 % and 48.4% over the control, respectively (Fig. 3c). Similarly, the highest NP rate 138/92 kg /ha increased Ava.P to 9.91 ppm at Site 1 and 11.17 at site 2 (Fig. 3d), corresponding to increase of 51.3% and 57.8% above the control. The enhancement of Ava.P can be attributed to direct phosphorus inputs, mineralization of organic P, reduced P fixation through organic acid release, and improved microbial activity associated with VC application. Site 2 consistently exhibited higher Ava.P than Site 1, likely due to its relatively higher initial P status and slightly higher pH, which reduced P fixation under acidic conditions [17]. These findings are consistent with previous studies demonstrating that integrated application of organic and inorganic fertilizers improves soil phosphorus availability and P-use efficiency [24, 49, 51, 57].



Note: Bars sharing the same letter within site are not significantly different at ($P \leq 0.05$)

Fig. 3 Effect of VC on Soil organic carbon (OC), cation exchange capacity (CEC), bulk density (BD), and total porosity

3.3.4. Soil Organic Carbon (OC)

Soil organic carbon (OC) was significantly ($P \leq 0.01$) affected by VC application at both experimental sites, whereas NP fertilizer and its interaction with VC had no significant effect on OC (Table 4). Soil OC increased progressively with increasing VC rates, reaching the highest values at 9 t/ha VC (1.48% at Site 1 and 1.93% at Site 2), compared with 1.23% and 1.53% in the control treatments (Fig. 4a), representing increases of 20.3% and 26.1%, respectively (Fig. 4a). Site 2 consistently exhibited higher OC than Site 1, likely due to its relatively favorable initial soil conditions. The increase in soil OC is attributed to the direct addition of stabilized organic matter and enhanced humification associated with VC, whereas inorganic NP fertilizers contributing little to soil carbon accumulation. These findings agree with previous experimental studies reporting improved soil OC following VC application and highlight the

importance of organic amendments in enhancing soil organic carbon stocks and soil fertility status [23, 58-61].

3.3.5. Soil Cation Exchange Capacity (CEC)

Soil cation exchange capacity (CEC) was significantly ($P \leq 0.01$) affected by VC application at both study sites, whereas NP fertilizer and its interaction with VC had no significant effect on CEC (Table 4). CEC increased progressively with increasing VC rates (Fig. 4b), reaching maximum values of 30.41 cmol (+)/kg of soil and 27.52 cmol (+)/kg of soil at Site 1 and Site 2, respectively, under 9 t/ha VC, compared with 27.41 cmol (+)/kg of soil and 23.67 cmol (+)/kg of soil the control treatments (Fig. 4b). this corresponded to increase of 11% and 16%, respectively. The improvement in CEC could be attributed to the addition of organic matter rich in negatively charged functional groups (-COOH, -OH), which enhances cation exchange sites and nutrient retention capacity [9]. The non-significant effect of NP fertilizer suggests that CEC enhancement was primarily governed by organic matter inputs rather than mineral fertilizers [17, 44]. Similarly, increases in CEC following VC application have been reported by Safadoust et al [49], Teka et al.[62], and Regasa et al. [63] , confirming the positive role of VC in improving soil exchange properties and overall soil fertility.

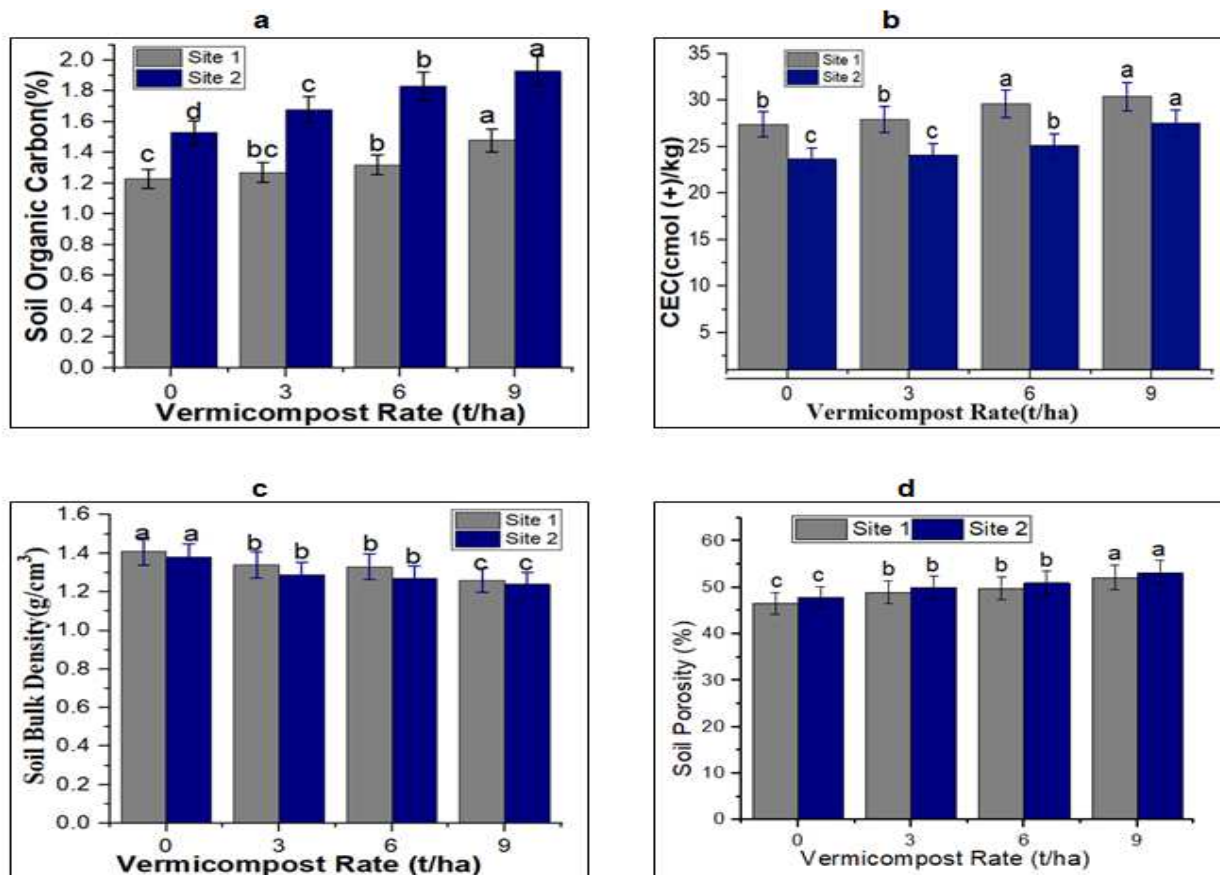
3.3.6. Soil Bulk Density (BD)

Soil bulk density (BD) was significantly ($P \leq 0.01$) influenced by VC application at both experimental locations, whereas NP fertilizer and its interaction with VC showed non-significant effect on BD (Table 4). Bulk density decreased progressively with increasing VC rates (Fig. 4c), with the highest values recorded in the control treatment (1.41 and 1.38 g/cm³ at Site 1 and Site 2 ,respectively) and the lowest values under 9 t/ha VC (1.26 and 1.24 g/cm³), representing reduction of 10.65 and 10.1% , respectively (Fig. 4c). The decline in BD could be attributed to improved soil aggregation and increased porosity resulting from organic matter incorporation from VC added, which enhances aeration, water infiltration, and root growth [9]. The non-significant effect of NP fertilizer indicates that improvements in soil physical properties were primarily derived by VC application. Similar reductions in soil BD following VC application have been reported by

Safadoust et al.[49], Raj et al. [64], Alfaraj et al.[65], and Sarhan and Al-alawy [66], highlighting the importance of organic amendments in alleviating soil compaction and improving soil physical quality.

3.3.7. Soil Total Porosity

Soil porosity was significantly ($P \leq 0.05$) influenced by VC application at both experimental locations, whereas NP fertilizer and its interaction with VC showed non-significant effect on soil total porosity (Table 4). The total porosity of soil increased progressively with increasing VC rates, ranging from 46.6 to 52.1% at Site 1 and from 47.8 to 53.2% at site 2 as VC rates increased from 0 to 9 t/ha (Fig. 4d). Compared with the control treatment, the highest VC rate (9 t/ha) increased total porosity by approximately 12% and 11% at Sites 1 and 2, respectively.



Note: Bars sharing the same letter within site are not significantly different at ($P \leq 0.05$)

Fig. 4 Effect of VC on Soil organic carbon (OC), cation exchange capacity (CEC), bulk density (BD), and total porosity

The improvement in soil porosity is likely attributed to the addition of organic matter, which enhances soil aggregation, reduces compaction, increases pore spaces, and increases water retention capabilities [67]. The observed increase in porosity is consistent with the concurrent reduction in BD and reflects the positive effect of VC on soil structural quality. Similar findings were reported by Melak et al [24] and Gobena et al [51], who reported that VC application improved soil porosity through enhanced organic matter accumulation and aggregate stability. These results suggest that VC is an effective amendment for improving the physical condition of agricultural soil.

3.4. Wheat Response to Integrated Vermicompost (VC) and NP Fertilizer Application

3.4.1. Plant Height (PH)

Plant height (PH) was significantly ($P \leq 0.01$) influenced by VC, NP fertilizer, and their interaction at both experimental sites (Table 5). The tallest plants were observed from the combined application of 9 t /ha VC with 138/92 kg /ha NP fertilizer, recording 90.3 cm at Site 1 and 94.9 cm at Site, where the absolute control produced the shortest plants (49.1cm and 51.5 cm, respectively (Table 6). This integrated treatment increased PH by 83.9% and 84.3% over the control and by 12.0% and 11.8% compared with the recommended NP fertilizer applied alone at Site 1 and Site 2, respectively. The enhanced PH under integrated nutrient application may be attributed to the synergistic effects of readily available nutrients from mineral fertilizers and the improvement of soil conditions, microbial activity, nutrient retention, and gradual nutrient release from VC, which collectively promote vegetative growth (Fig. 5 and Fig. 6). Similar findings have been reported by Melak et al. [24], who observed greater wheat PH under combined VC and mineral N application, and by CIRKA *et al* [68] and Aslam *et al* (2023[69] ,who also documented superior wheat growth following integrated VC and mineral fertilizer application.

Table 5 ANOVA showing the effect of integrated VC and NP Fertilizer application on bread wheat

SV	Plant height (PH)		Spike length (SL)		Kernels per spike (KS)		1000-seed weight (TSW)	
	Site1	Site2	Site1	Site2	Site 1	Site2	Site1	Site2
VC	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0011
NP	<0.0001	<0.0001	<0.0001	<0.0001	0.0002	<0.0001	<0.0001	0.0026
VC×NP	0.0002	0.0004	0.0003	0.0023	0.0431	0.0012	0.0440	0.0123
Site	<0.0001		0.04100		<0.0001		<0.0001	
SV	Grain yield (GY)		Straw yield (SY)		Biomass (BM)			
	Site 1	Site2	Site1	Site2	Site1		Site2	
VC	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001		<0.0001	
NP	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001		<0.0001	
VC×NP	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001		<0.0001	
Site	<0.0001		<0.0001		<0.0001			

Where, SV=source of variations, VC=vermicompost, N=Nitrogen, P= Phosphorus, ns= non-significant at $p > 0.05$, * =significant at $P \leq 0.05$, **=significant at $P \leq 0.01$.

3.4.2. Spike Length (SL)

Wheat spike length (SL) was significantly ($P \leq 0.01$) affected by VC, NP fertilizer, and their interaction at both study locations (Table 5). The longest spikes were obtained from the combined application of 9 t /ha VC with 138/92 kg /ha NP fertilizer, measuring 8.7 cm at Site 2 and 8.98 cm at Site 2, whereas the absolute control produced the shortest (4.4 cm and 4.5 cm, respectively (Table 6). These values represented increases of 97.7% and 97.8% over the control treatment at the experimental Site 1 and 2, respectively; however, they did not differ significantly from the recommended NP fertilizer applied alone. The improvement in spike length under integrated nutrient application may be attributed to enhanced nutrient availability; particularly nitrogen and phosphorus, improved assimilate production and translocation to reproductive organs, and the favorable effects of VC on soil conditions. Conversely, reduced SL under

unfertilized treatments was likely associated with nutrient deficiency and poor soil conditions that restricted plant growth as shown in Fig. 5 and Fig. 6. Similar findings have been reported by Workineh & Kitila [61], Hadis et al [70], and Yitbarek et al [71], who documented superior SL under the combined application of VC and mineral fertilizers, highlighting the synergistic benefits of integrated nutrient management on bread wheat reproductive development.

3.4.3. Kernels per spike (KS)

Kernels per spike (KS), also referred as grains per spike, is the average number of fully developed kernels produced on a single spike of bread wheat. It is an important yield component that reflects the reproductive efficiency of the crop and is determined by the number of fertile florets that successfully undergo pollination and grain during spike developments [72]. Kernels per spike was significantly ($P \leq 0.01$) affected by both VC, NP fertilizers, and their interactions at $p \leq 0.05$ as shown in Table 5. The highest KS was obtained from the combined application of 9 t /ha VC with 138/92 kg /ha NP fertilizer, recording 50.8 seeds/kernels at Site1 and 57.2 kernels at Site 2, whereas the lowest (21.1 at Site 1 and 22.7 at Site 2) were recorded from the control treatment (Table 6). Compared to the with the absolute control, this treatment increased KS by 141% at Site 1 and 152% at site 2, and 17.6% and 17.7%, respectively, over the recommended NP fertilizer applied alone. The enhanced kernel number under integrated nutrient application may be attributed to improved nutrient availability, particularly Nitrogen and phosphorus, which promotes floret fertility, spike development, and grain set during critical reproductive stages. Similar results have been reported by CIRKA et al [68], Oyege and Balaji Bhaskar [73], and Singh et al [74], who observed greater kernel/grain numbers under combined application of VC and mineral fertilizers. These findings suggest that integrated organic and inorganic nutrient sources enhances reproductive performances through balanced and sustained nutrient supply, improved nutrient use efficiency, and the provision of growth-promoting substances [20]. Higher kernel numbers generally indicate improved assimilate partitioning and enhanced grain production potential, provided that sufficient resources are available for grain filling [72]

Table 6 Interaction effect of VC and NP fertilizer on Plant height (PH), spike length (SL), kernel number (KS), and Thousand seed weight (TSW) of wheat

Treatments		PH (cm)		SL (cm)		KS(number)		TSW(g)	
VC	N/P ₂ O ₅	Site1	Site2	Site1	Site2	Site1	Site2	Site1	Site2
0	0/0	49.1 ^j	51.5 ⁱ	4.4 ^h	4.5 ^h	21.1 ^g	22.7 ^f	26.0 ^{fg}	28.6 ^{fg}
	46/46	75.7 ^{fg}	76.2 ^f	7.0 ^e	7.2 ^e	36.3 ^{ef}	40.2 ^{de}	28.3 ^{ef}	31.1 ^{ef}
	92/69	78.2 ^{ef}	82.1 ^e	7.6 ^{de}	7.8 ^{de}	40.3 ^{cde}	45.3 ^{cd}	28.2 ^{ef}	31.0 ^{ef}
	138/92	80.3 ^{de}	84.3 ^{de}	8.2 ^{abcd}	8.4 ^{abc}	43.2 ^{bcd}	48.6 ^{bc}	30.2 ^{de}	33.3 ^{de}
3	0/0	54.0 ⁱ	56.8 ^h	5.2 ^g	5.3 ^g	22.6 ^g	25.4 ^f	25.7 ^g	28.3 ^g
	46/46	79.0 ^{ef}	82.9 ^e	8.0 ^{bcd}	8.2 ^{bcd}	34.9 ^{ef}	39.2 ^{de}	28.1 ^{ef}	30.9 ^{ef}
	92/69	85.5 ^{bc}	89.8 ^{bc}	8.1 ^{abcd}	8.3 ^{abcd}	44.1 ^{bcd}	49.7 ^{bc}	30.9 ^d	34.0 ^d
	138/92	86.3 ^{abc}	90.6 ^{abc}	8.3 ^{abc}	8.5 ^{abc}	46.1 ^{abc}	51.9 ^{ab}	32.4 ^{cd}	35.7 ^{cd}
6	0/0	62.9 ^h	66.1 ^h	5.9 ^f	6.0 ^f	32.0 ^f	36.0 ^e	28.5 ^e	31.3 ^e
	46/46	79.6 ^{ef}	83.7 ^e	7.7 ^{cde}	7.9 ^{cde}	39.8 ^{de}	44.8 ^{cd}	31.8 ^{cd}	35.0 ^{cd}
	92/69	85.0 ^{bc}	89.3 ^{bc}	8.4 ^{ab}	8.6 ^{ab}	46.3 ^{ab}	52.1 ^{ab}	33.5 ^{bc}	36.8 ^{bc}
	138/92	88.7 ^{ab}	93.1 ^{ab}	8.5 ^{ab}	8.7 ^{ab}	47.7 ^{ab}	53.7 ^{ab}	35.4 ^{ab}	38.9 ^{ab}
9	0/0	72.1 ^f	75.7 ^f	6.2 ^f	6.4 ^f	38.9 ^{de}	43.7 ^{cd}	30.5 ^{de}	33.5 ^{de}
	46/46	83.9 ^{cd}	88.1 ^{cd}	7.9 ^{bcd}	8.1 ^{bcd}	42.3 ^{bcd}	47.7 ^{bc}	33.5 ^{bc}	36.8 ^{bc}
	92/69	87.8 ^{abc}	92.2 ^{abc}	7.9 ^{bcd}	8.1 ^{bcd}	47.1 ^{ab}	53.0 ^{ab}	34.2 ^{bc}	37.6 ^{bc}
	138/92	90.3 ^a	94.9 ^a	8.7 ^a	8.9 ^a	50.8 ^a	57.2 ^a	36.9 ^a	40.7 ^a
P-value		0.0002	0.0003	0.0002	0.0486	0.0441	0.0430	0.0410	0.0420
CV (%)		3.3	3.3	5.6	5.3	8.9	8.9	4.7	4.6

Where, VC=vermicompost rate (t/ha), NP=nitrogen and phosphorus fertilizer rate (kg/ha) and P in the form of P₂O₅, PH=plant height (cm), SL=spike length (cm), KS=number of kernels per spike, TSW=thousands seed weight (g), ha=Hectare, CV=coefficient of variation; Means followed by the same letters within a column are not significantly different at $P \leq 0.05$.

3.4.4. Thousand-Seed Weight (TSW)

Thousand-seed weight (TSW), an indicator of grain filling efficiency and grain quality, was significantly ($P \leq 0.01$) affected by VC, and NP fertilizer application, as well as by their interaction ($P \leq 0.05$) (Table 5). At Site 1, TSW increased from 26.0 g in the control

to 39.9 g in 9 t/ha VC combined with 138/92 kg /ha NP fertilizer (Table 6), representing increases of 41.9% over the control and 22.1% over the recommended NP rate alone. Similarly, at Site 2, thousand seed weight (TSW) increased from 28.6 g to 40.7 g under the same treatment (Table 6), corresponding to increases of 42.3% and 22.2%, respectively. The enhanced TSW under integrated nutrient application may be attributed to balanced nutrient supply that improved assimilate translocations and grain filling, resulting in heavier and well-developed grains. These findings agree with those of Workineh & Kitila [61], Basir et al [75], and Yadav et al [76], who reported also significant improvements in TSW under integrated VC and Mineral fertilizer application, likely due to sustained nutrient release, improved soil moisture retention, and enhanced soil biological activity [77]

3.4.5. Aboveground Biomass Yield (BM)

Biomass yield (BM), an indicator of total aboveground dry matter production, was significantly ($P \leq 0.01$) affected by VC, NP fertilizer, and their interaction (Table 5). The highest BM was obtained from the combined application of 9 t/ha VC and 138/92 kg /ha NP fertilizer, producing 11.0 t /ha at Site 1 and 12.1 t/ha at Site 2, whereas the lowest BM was recorded in the unfertilized control (1.9 t/ha and 2.2 t/ha, respectively) presented in Table 7. This corresponded to increases of 481% and 438% over the control, and 101.6% and 81.8% over the recommended NP fertilizer at Site 1 and 2, respectively. The enhanced BM production under integrated nutrient management may be explained by the complementary effect of VC and mineral fertilizers, whereby VC improves soil physical conditions, microbial activity, nutrient retention, and gradual nutrient release, while NP fertilizers provide readily available nutrients for crop growth and performances as shown in Fig. 5 and Fig. 6. The consistently higher BM with increasing NP rates across VC levels further indicates a synergistic effect between organic and inorganic nutrient sources. The present results corroborate earlier findings reported by Teshome Yitbarek et al [71], Molla Hadis et al [70], Gemeda et al [78], Ahmad and Tripathi [79], and Workineh & Kitila (2024) [61], who documented enhanced wheat BM production following integrated VC and mineral fertilizer application.

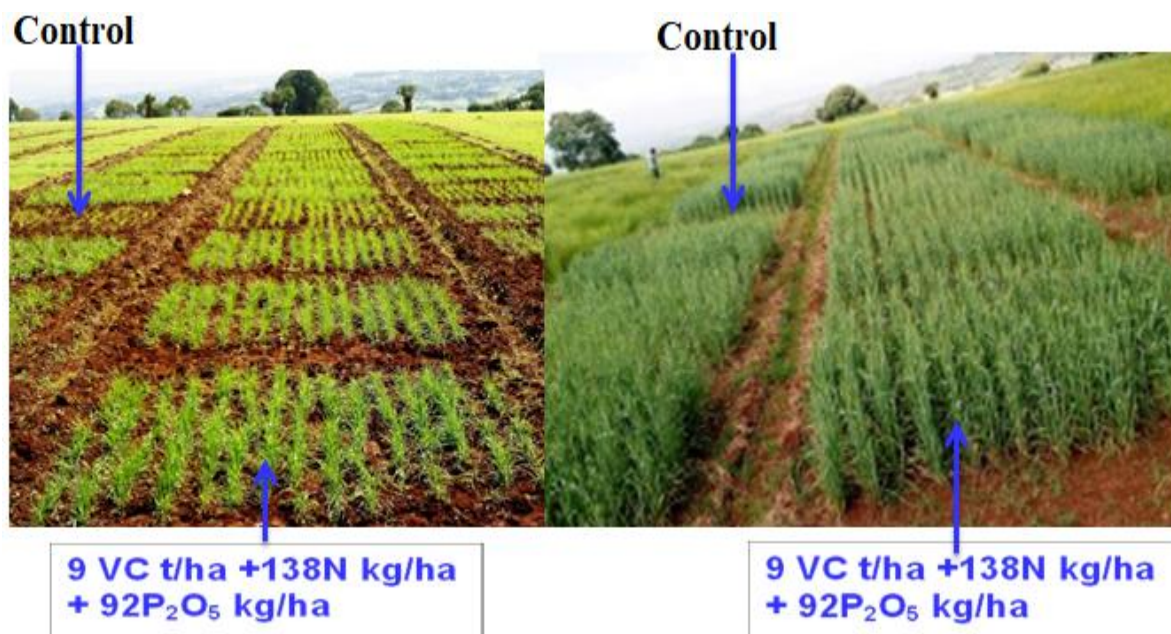


Fig. 5 Vegetative performance response of bread wheat to integrated application of VC and NP fertilizers at *Adet Hana Kebele* /Site 1

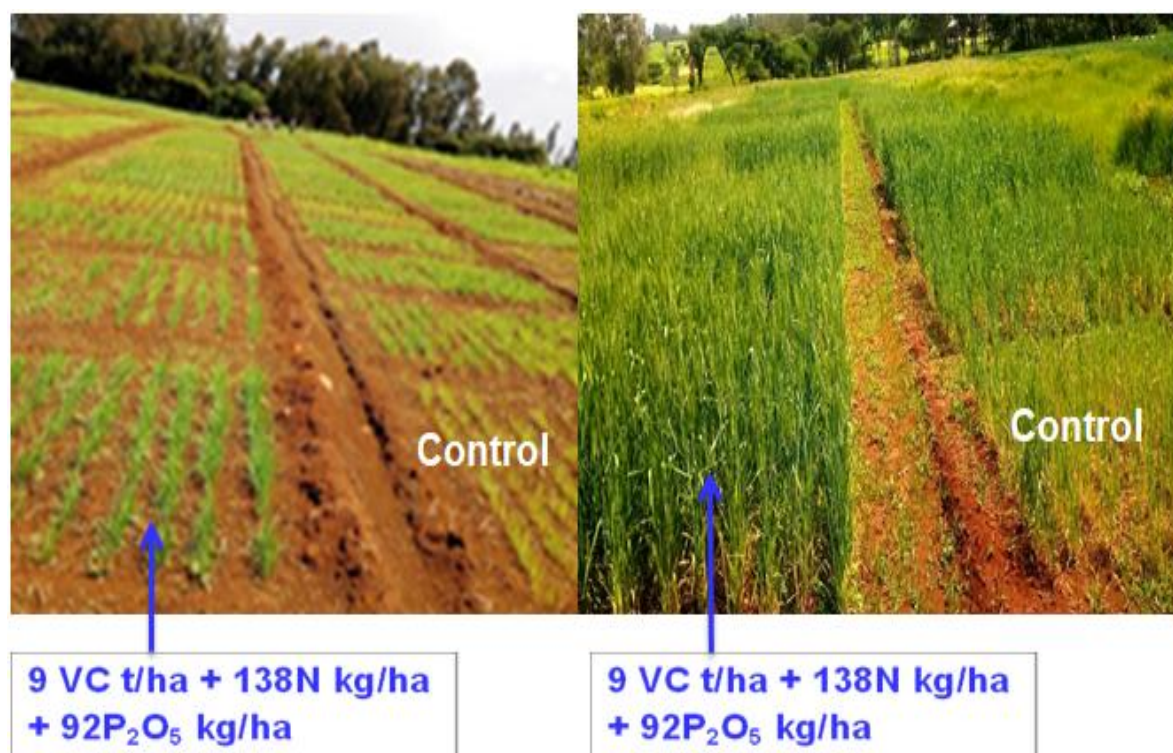


Fig. 6 Vegetative performance response of bread wheat to integrated application of VC and NP fertilizers at *Mosebo Kebele* /Site 2

3.4.6. Grain Yield (GY)

Grain yield (GY), the principal economic trait in wheat production, was significantly ($P \leq 0.01$) influenced by VC, NP fertilizer, and their interaction (Table 5). The highest GY was gained from the combined application of 9 t/ha VC and 138/92 kg /ha NP fertilizer, producing 5.0 t/ha at Site 1 and 5.6 t/ha at Site 2, whereas the unfertilized control recorded the lowest yields (0.7 t/ha and 0.8 t/ha, respectively) detailed in Table 7. This represented yield increases of 631% and 640% over the control and 105% and 71% over the sole recommended NP fertilizer at Site 1 and 2, respectively. The improved GY following integrated nutrient application could be due to improved yield components, greater nutrient uptake efficiency, and better assimilate partitioning to grains, while nutrient limitations under the control and lower fertilizer rates likely restricted tillering, spike development, grain filling, finally led to GY reduction. Similar trends have been documented by Karan et al.[80]), Gosa et al. [81], Ahmad and Tripathi [79], Weldegebriel Gebrehiwot et al [82] and Ebrahim [83], who reported increased GY following integrated VC and NP fertilizer applications.

3.4.7. Straw Yield (SY)

Straw yield (SY) was significantly ($P \leq 0.01$) affected by VC, NP fertilizer, and their interaction (Table 5). The highest SY was obtained from the combined application of 9 t/ha VC and 138/92 kg /ha NP fertilizer, providing 6.0 t/ha at Site 1 and 6.5 t/ha at Site 2, whereas the lowest SY was recorded in the control treatments (1.2 t/ha and 1.5 t/ha at Site 1 and 2 ,respectively), shown in Table 7. This represented increases of 398% and 336% over the control and 99% and 93% over the sole recommended NP treatment at Site 1 and 2, respectively. The improved SY production following integrated VC and NP fertilizer application may be attributed to improved nutrient availability, reduced soil acidity, and better soil physical conditions, which collectively promoted vegetative growth (Fig. 5 and Fig. 6) and biomass accumulation. Similar findings have been reported by Agegnehu et al.[25], Melak et al. [24], Ejigu et al.[54], Ahmad and Tripathi [79], Gemeda et al. [78], and Ali et al. [84], who demonstrated that integrating organic amendments with mineral fertilizers significantly improves wheat straw and overall biomass production.

Table 7 The Interaction effect of VC and NP fertilizer on BM, GY and SY of Wheat

Treatments		BM(t/ha)		GY(t/ha)		SY(t/ha)	
VC	N/P ₂ O ₅	Site1	Site2	Site1	Site2	Site1	Site2
0	0/0	1.9 ^j	2.2 ^j	0.7 ^j	0.8 ⁱ	1.2 ^j	1.5 ^j
	46/46	4.1 ^h	4.5 ^h	1.6 ^h	1.8 ^g	2.5 ^h	2.7 ^{hi}
	92/69	5.2 ^g	5.8 ^g	2.3 ^g	2.6 ^f	2.9 ^{fg}	3.3 ^{fg}
	138/92	5.5 ^g	6.6 ^f	2.4 ^{fg}	3.2 ^d	3.0 ^f	3.4 ^f
3	0/0	2.4 ^j	2.6 ^j	0.9 ^j	1.0 ⁱ	1.5 ^j	1.6 ^j
	46/46	4.4 ^h	4.8 ^h	1.7 ^h	1.9 ^g	2.7 ^{fgh}	3.0 ^{gh}
	92/69	7.2 ^e	7.9 ^e	3.2 ^e	3.5 ^d	4.1 ^{cd}	4.4 ^d
	138/92	7.8 ^d	8.6 ^d	3.6 ^d	4.1 ^c	4.2 ^c	4.5 ^d
6	0/0	3.3 ⁱ	3.6 ⁱ	1.2 ^j	1.4 ^h	2.1 ⁱ	2.3 ^j
	46/46	6.2 ^f	6.8 ^f	2.6 ^{fg}	2.8 ^{ef}	3.7 ^e	4.0 ^e
	92/69	9.2 ^c	10.0 ^c	3.9 ^c	4.3 ^c	5.2 ^b	5.7 ^c
	138/92	9.8 ^b	10.7 ^b	4.3 ^b	4.7 ^b	5.5 ^b	6.0 ^{bc}
9	0/0	4.3 ^h	4.7 ^h	1.7 ^h	1.9 ^g	2.6 ^{gh}	2.8 ^h
	46/46	6.5 ^f	7.1 ^f	2.6 ^f	2.9 ^e	3.8 ^{de}	4.2 ^{de}
	92/69	9.8 ^b	11.0 ^b	4.2 ^b	4.8 ^b	5.6 ^b	6.2 ^{ab}
	138/92	11.0 ^a	12.1 ^a	5.0 ^a	5.6 ^a	6.0 ^a	6.5 ^a
P-value		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
CV (%)		5.6	5.5	6.1	5.7	6	6.2

Where, VC=vermicompost rate (t/ha), NP=nitrogen and phosphorus fertilizer rate (kg/ha) and P in the form of P₂O₅, BM=aboveground biomass (t/ha), GY=grain yield (t/ha), SY=straw yield (t/ha), ha=Hectare, CV=coefficient of variation; Means followed by the same letters within a column are not significantly different at P ≤ 0.05.

3.4.8. Correlation among Growth, Yield and Yield Components

Crop yield is the result of the cumulative interaction among various dependent and independent variables (traits), where the expression of yield is influenced by the combined effect of genetic, physiological, environmental, and management-related factors within an experiment [85]. Pearson coloration analysis revealed strong and positive significant ($P \leq 0.01$) association among all bread wheat traits at both experimental locations/sites (Table 8). The strong positive correlation coefficient (r) among yield components at both sites (Table 8), indicate that improving any traits such as PH,SL,BM,KS,TSW,SL may indirectly enhance grain and other yields. Integrated application of VC and NP fertilizers may strengthen these relationships by improving nutrient use efficiency, particularly nitrogen and phosphorus availability, thereby promoting coordinated yield development [21, 25]

Site 1							
	BM	GY	SY	PH	SL	KS	TSW
BM	1						
GY	0.997**	1					
SY	0.998**	0.990**	1				
PH	0.878**	0.874**	0.878**	1			
SL	0.831**	0.832**	0.826**	0.971**	1		
KS	0.918**	0.920**	0.912**	0.967**	0.920**	1	
TSW	0.946**	0.935**	0.952**	0.837**	0.765**	0.898**	1
Site 2							
	BM	GY	SY	PH	SL	KS	TSW
BM	1						
GY	0.994**	1					
SY	0.995**	0.978**	1				
PH	0.890**	0.891**	0.880**	1			
SL	0.839**	0.851**	0.819**	0.973**	1		
KS	0.914**	0.920**	0.898**	0.970**	0.922**	1	
TSW	0.943**	0.926**	0.948**	0.848**	0.771**	0.894**	1
** Correlation(r) is significant at the 0.01 level (2-tailed).							

* Correlation (r) is significant at the 0.05 level (2-tailed).

Where, BM=Biomass, GY=Grain yield, SY=Straw yield, PH=Plant height, KS=Kernels per spike, TSW=Thousand-seed weight

3.4.9. Partial Budget Analysis Based on Combined Yield Data across the Study Sites

Table 9 Partial budget and dominance analysis results of bread wheat yields

Treatments combination		Yields		TVC	GB	NB	D	MRR (%)
VC	N/P ₂ O ₅	GY	SY					
0	0/0	0.72	1.35	0	52087.5	52087.5		-
3	0/0	0.92	1.56	6000	66350	60350		137.7
6	0/0	1.29	2.15	12000	92987.5	80987.5		344
0	46/46	1.71	2.56	13151.2	122900	109748.8		2498.3
9	0/0	1.79	2.70	18000	128675	110675		19.1
3	46/46	1.81	2.83	19151.2	130237.5	111086.3		35.7
0	92/69	2.44	3.10	23161.5	174675	151513.6		1008.1
6	46/46	2.70	3.82	25151.2	193775	168623.8		859.9
3	92/69	3.31	4.25	29161.5	237012.5	207851.1		978.2
9	46/46	2.76	4.02	31151.2	198225	167073.8	D	-
0	138/92	2.83	3.20	33171.7	202100	168928.3		-970.6
6	92/69	4.13	5.48	35086.8	295950	260863.2		4800.5
3	138/92	3.85	4.37	39171.7	274962.5	235790.8	D	-
9	92/69	4.51	5.90	41161.5	323075	281913.6		346.5
6	138/92	4.49	5.73	45171.7	321462.5	276290.8	D	-
9	138/92	5.26	6.26	51171.7	376025	324853.3		429

Where, VC=Vermicompost rate(t/ha), N=Nitrogen fertilizer(kg/ha), P₂O₅=Phosphorus fertilizer(kg/ha), GY=Grain Yield(t/ha), SY=straw yield(t/ha), TVC=Total variable cost in Ethiopian Birr per hectare, GB=Gross benefit in Ethiopian Birr per hectare, NB= Net benefit in Ethiopian Birr per hectare, D=Dominated, MRR= Marginal rate of return (%); Cost of VC was two(2) Birr/kg, N was 149.33 Birr/kg, P₂O₅ estimated by cost of Di-ammonium phosphate (DAP) which

was 89.7 Birr/kg & N from DAP was assumed & calculated, wheat GY was 70 Birr/kg, wheat SY was 1.25 Birr/kg.

Because the yield response at the two experimental locations /Sites were consistent and followed similar trends (Table 6 and Table 7), with the same treatments producing the highest and lowest values of BM GY, SY, and other major yield components (Table 7 and Table 6), the partial budget and dominance analysis were conducted using the combined yield data from both locations/sites. This approach provided a more robust evaluation of economic feasibility and profitability of the tested treatments and supported recommendations applicable to farmers and other stakeholder within the study district and comparable agro-ecological areas.

Partial budget analysis using pooled data across two experimental sites showed that the combined application of 9 t/ha VC and 138N/92 P₂O₅ kg/ha generated the highest net benefit (324,853.3 Ethiopian Birr (ETB) /ha) with an acceptable marginal rate of return (MRR) of 429% (Table 9), indicating that each additional 1 ETB invested returned 4.29 ETB in profit. The combination of 9 t/ha VC and 92N/69 P₂O kg/ha provided the second-highest net benefit (281,913.6 ETB) with an MRR of 346%. In contrast, minimum net benefit (5, 2087.5 ETB) was recorded from the control treatment. Similarly, sole application of either VC or NP fertilizer resulted in lower economic returns (Table 9).The dominated (D) treatments were excluded from further economic analysis (Table 9). Non-dominated treatments with MRR values greater than 100% were economically acceptable, demonstrating their feasibility for adoption and recommendation([41].

4. Conclusion

This study conclusively demonstrated that the integrated application of vermicompost (VC) with inorganic nitrogen (N) and phosphorus (P) fertilizers is a highly effective strategy for sustainable wheat production in Yilmana Densa district of Northwestern Ethiopia. The synergistic effect of combined application significantly outperformed the sole application of either input in terms of soil fertility improvement, crop yield enhancement, nutrient use efficiency, and economic returns. The combined application of 9 t/ha VC with 138 N/92 P₂O₅ kg/ha fertilizer proved to be the most effective

treatment, achieving the highest biomass (BM), grain (GY), and straw yields (SY), and net benefits (324,853.3 ETB/ha). This integrated approach also significantly improved key soil physicochemical properties, including pH, organic carbon (OC), total nitrogen (TN), available phosphorus (Ava.P), cation exchange capacity (CEC), bulk density (BD) and total porosity. These soil improvements mainly derived from VC applications. The overall results in this study confirmed that integrated soil fertility management (ISFM), through the combined use of organic and inorganic nutrient sources, is a sustainable strategy for enhancing soil health, improving nutrient use efficiency, increasing crop productivity, and boosting smallholder farmers' profitability.

5. Recommendation

Based on the economic analysis across combined experimental sites, the following recommendations are suggested for the study area and similar agro-ecological environments:

- The combined application of 9t /ha VC with 138N/92P₂O₅ kg/ha fertilizer is recommended as the most economically profitable treatment for bread wheat production under the study conditions, as it provided the highest net benefit and acceptable marginal rate of return.
- For farmers with limited financial resources, the combined application of 9t/ha vermicompost with 92N/69 P₂O₅ kg /ha fertilizer or 6 t /ha VC with 92 N/69 P₂O₅ kg /ha fertilizer can be considered as the second and third alternative options, respectively, as they offer higher economic returns with relatively lower initial input costs.
- Farmers should adopt the integrated use of inorganic fertilizers together with organic fertilizers or amendments to maintain soil health and enhance crop productivity.
- Further long-term and multi-location trials should be conducted to evaluate and validate the consistency of the residual effect of integrated VC and NP fertilizer application on soil properties, crop productivity, and nutrient use efficiency over time and different agro-ecological conditions.

- The integrated application of VC and inorganic fertilizer should be included in the national soil fertility and agricultural policies to promote sustainable soil health and crop production, if not included.

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Data Availability

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

Declarations

Ethics Approved and Consent to Participate

All plant measurements, agronomic data, and soil sample data collection procedures were conducted in accordance with the Ethiopian national guidelines and standards for soil and agronomic data collection.

Consent for Publication

Not applicable

Competing Interest

The authors declare that they have no known competing interests or personal relationships that could have influenced the work reported in this manuscript.

References

1. FAO. *Healthy soils are the basis for healthy food production*. 2015; Available from: <http://www.fao.org/3/i6874e/i6874e.pdf>.
2. Lal, R., *Soil organic matter content and crop yield*. Journal of Soil and Water Conservation, 2020. **75**(2): p. 27A–32A.
3. ESS, *Ethiopia Socioeconomic Panel Survey (ESPS) Report - Wave 5, 2021/22*. 2023.
4. NBE, 'Annual report 2022/23'. Addis Ababa, Ethiopia. Retrieved from: <https://nbe.gov.et/annual-report/>; Accessed on 26/01/2026, 2023.
5. Hailu, H., et al., *Soil fertility status and wheat nutrient content in Vertisol cropping systems of central highlands of Ethiopia*. Agriculture & Food Security, 2015. **4**(1): p. 19.
6. Agegnehu, G. and T. Amede, *Integrated soil fertility and plant nutrient management in tropical agro-ecosystems: a review*. Pedosphere, 2017. **27**(4): p. 662–680.
7. Zelleke, G., et al., *Fertilizer and soil fertility potential in Ethiopia*. Gates Open Res, 2019. **3**(482): p. 482.

8. Hailelassie, A., et al., *Assessment of soil nutrient depletion and its spatial variability on smallholders' mixed farming systems in Ethiopia using partial versus full nutrient balances*. Agriculture, ecosystems & environment, 2005. **108**(1): p. 1–16.
9. Brady, R.R.W.a.N.C., *The nature and properties of soils (15th ed., Global ed.)*. Pearson Education Limited., 2017.
10. Desta, G., et al., *Effects of land management practices and land cover types on soil loss and crop productivity in Ethiopia: A review*. International Soil and Water Conservation Research, 2021. **9**(4): p. 544–554.
11. Selassie, Y.G., F. Anemut, and S. Addisu, *The effects of land use types, management practices and slope classes on selected soil physico-chemical properties in Zikre watershed, North-Western Ethiopia*. Environmental Systems Research, 2015. **4**(1): p. 3.
12. Golla, A.S., *Soil acidity and its management options in Ethiopia: A review*. International Journal of Scientific Research and Management, 2019. **7**(11): p. 1429–1440.
13. Hurni, H., et al., *Global change and sustainable development*. Bern: University of Bern, 2010: p. 187–207.
14. GIZ, *Lessons and Experiences in Sustainable Land Management. Ethiopia's Sustainable Land Management Program*. Bonn and Eschborn: Deutsche Gesellschaft für Internationale Zusammenarbeit, GmbH. <https://nrmdblog.files.wordpress.com/2016/09/giz2015-en-lessons-experiencesustainable-land-management-ethiopia.pdf>., 2015.
15. Elias, E., P. Okoth, and E. Smaling, *Explaining bread wheat (Triticum aestivum) yield differences by soil properties and fertilizer rates in the highlands of Ethiopia*. Geoderma, 2019. **339**: p. 126–133.
16. Tamene, L., et al., *A review of soil fertility management and crop response to fertilizer application in Ethiopia: towards development of site-and context-specific fertilizer recommendation*. 2017.
17. Havlin, J.L., et al., *Soil fertility and fertilizers*. 2016: Pearson Education India.

18. Vanlauwe, B., et al., *Integrated soil fertility management: operational definition and consequences for implementation and dissemination*. Outlook on agriculture, 2010. **39**(1): p. 17–24.
19. Vanlauwe, B., et al., *Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation*. Soil, 2015. **1**(1): p. 491–508.
20. Domínguez, J. and C. Edwards, *Biology and ecology of earthworm species used for vermicomposting. Chapter 3: 27-40*. vermiculture technology. Earthworms, organic wastes, and environmental management. Edwards, CA, 2011.
21. Agegnehu, G., et al., *Benefits of biochar, compost and biochar–compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil*. Science of the Total Environment, 2016. **543**: p. 295–306.
22. Ejigu, W., et al., *Integrated fertilizer application improves soil properties and maize (*Zea mays* L.) yield on Nitisols in Northwestern Ethiopia*. Heliyon, 2021. **7**(2).
23. Lazcano, C. and J. Domínguez, *The use of vermicompost in sustainable agriculture: impact on plant growth and soil fertility*. Soil nutrients, 2011. **10**(1-23): p. 187.
24. Melak, E., et al., *Wheat yield and soil physicochemical properties through mineral nitrogen and vermicompost application in Lasta district, North Ethiopia*. Scientific Reports, 2025. **15**(1): p. 32906.
25. Agegnehu, G., P.N. Nelson, and M.I. Bird, *Crop yield, plant nutrient uptake and soil physicochemical properties under organic soil amendments and nitrogen fertilization on Nitisols*. Soil and Tillage Research, 2016. **160**: p. 1–13.
26. FAO. *The State of Food and Agriculture 2022: Leveraging Automation in Agriculture for Transforming Agrifood Systems*. <https://www.fao.org/newsroom/detail/FAO-state-of-food-andagriculture--SOFA-2022-automation-agrifood-systems/en>; Accessed on 24/01/2026. 2022.
27. Tisdale, S.L. and W.L. Nelson, *Soil fertility and fertilizers*. Soil Science, 1966. **101**(4): p. 346.

28. Snel, H., J. Glaser, and M. Schaap, *Yilmana Densa Woreda Food System Profile*. Stichting Wageningen Research Ethiopia. <https://edepot.wur.nl/701148>, 2023.
29. Ethiopian Meteorological Institute, E. *Weather and Climate Forecasting: Annual Climate Bulletin*. 2025.
30. Mulugeta, M. and T. Amsalu, *Gender, participation and decision making process in farming activities: The case of Yilman Densa District, Amhara Region, Ethiopia*. Journal of Economics and Sustainable Development, 2014. **5**(1): p. 28–34.
31. Derebe, B., et al., *Maximizing seed quality and seed yield of bread wheat (Tritium aestivum L.) through agronomic management in Amhara Region, Northwestern Ethiopia*. Journal of Tropical Crop Science Vol, 2022. **9**(2).
32. Abera, D., et al., *Guideline for agronomy and soil fertility data collection in Ethiopia: national standard*. 2020.
33. Bouyoucos, G.J., *Hydrometer method improved for making particle size analyses of soils 1*. Agronomy journal, 1962. **54**(5): p. 464–465.
34. Blake, G.† and K. Hartge, *Bulk density*. Methods of soil analysis: Part 1 Physical and mineralogical methods, 1986. **5**: p. 363–375.
35. van Reeuwijk, L.P., *Procedures for soil analysis*. (No Title), 1995.
36. Bremner, J.M. and C. Mulvaney, *Nitrogen—total*. Methods of soil analysis: part 2 chemical and microbiological properties, 1982. **9**: p. 595–624.
37. Bray, R.H. and L.T. Kurtz, *Determination of total, organic, and available forms of phosphorus in soils*. Soil science, 1945. **59**(1): p. 39–46.
38. Black, C., *Methods of Soil Analysis-Part 2* ASA pub. Madison, WI, 1965: p. 771–1572.
39. Sahlemedhin, S. and B. Taye, *Procedures for soil and plant analysis*. Technical paper, 2000. **74**: p. 110.
40. Gomez, K.A. and A.A. Gomez, *Statistical procedures for agricultural research*. 1984: John wiley & sons.
41. Program, C.E., *From agronomic data to farmer recommendations: An economics training manual*. 1988: CIMMYT.

42. Hazelton, P. and B. Murphy, *Interpreting soil test results: What do all the numbers mean?* 2025: CSIRO publishing.
43. Mesfin, A., *Nature and management of Ethiopian soils*. Alemaya University of Agriculture, Ethiopia, 1998. **272**.
44. Landon, J.R., *Booker tropical soil manual: a handbook for soil survey and agricultural land evaluation in the tropics and subtropics*. Routledge. 2014.
45. Elias, E. and G. Agegnehu, *Mineralogical and physicochemical properties of nitisols in the Ethiopian highlands*. Ethiopian Journal of Agricultural Sciences, 2020. **30**(4): p. 97–119.
46. WRB, I.U.o.S.S.W.G., *World Reference Base for Soil Resources 2022. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*. FAO, Rome. 2022.
47. Olsen, S.R., *Estimation of available phosphorus in soils by extraction with sodium bicarbonate*. 1954: US Department of Agriculture.
48. Color, M., *Munsell Soil-Color Charts: Grand Rapids*. 2009, MI.
49. Safadoust, A., S.B. Azimi, and M.B. Dehghan, *Restoring soil functionality in drylands: Soil texture-specific impacts of vermicompost as an organic waste-based amendment*. Journal of Arid Environments, 2025. **231**: p. 105446.
50. Abebe, A., et al., *Effects of lime, vermicompost, and blended fertilizer on maize (Zea mays L.) postharvest selected soil chemical properties in Assosa District, north-western Ethiopia*. Big Data in Agriculture, 2024. **6**(1): p. 36–43.
51. Gebrekidan, L., L. Wogi, and A. Chimdi, *Integrated effect of NPS and vermicompost addition on the selected soil properties at the Bako Agricultural Research Center in Gobu Sayo District Western Oromia, Ethiopia*. Discover Agriculture, 2025. **3**(1): p. 27.
52. Chen, L., et al., *Long-term straw return with reducing chemical fertilizers application improves soil nitrogen mineralization in a double rice-cropping system*. Agronomy, 2022. **12**(8): p. 1767.
53. Nigussie, A., et al., *Growth, nitrogen uptake of maize (Zea mays L.) and soil chemical properties, and responses to compost and nitrogen rates and their*

- mixture on different textured soils: Pot experiment*. Applied and Environmental Soil Science, 2021. **2021**(1): p. 9931763.
54. Ejigu, W., Y.G. Selassie, and E. Elias, *Integrated use of compost and lime enhances soil properties and wheat (*Triticum aestivum* L.) yield in acidic soils of Northwestern Ethiopia*. International Journal of Recycling of Organic Waste in Agriculture, 2023. **12**(2).
 55. Habtamu, M., et al., *Effects of integrated application of vermicompost and inorganic fertilizers on selected soil characteristics and productivity of wheat (*Triticum aestivum* L.) and faba bean (*Vicia faba* L.) in dire and legedadi watersheds of Ethiopia*. Applied and Environmental Soil Science, 2024. **2024**(1): p. 3163750.
 56. Yeasmin, S., et al., *Impact of Organic and Inorganic Sources of Nitrogen on Soil Fertility, Nitrogen Use Efficiency, and Carbon Accumulation Potential Under Subtropical Rice-Based Cropping Patterns in Farmers' Fields*. Nitrogen, 2025. **6**(3): p. 86.
 57. Fekadu, E., et al., *Organic and inorganic amendments on soil chemical properties at different period of incubation of acidic soil*. Eurasian Journal of Soil Science, 2018. **7**(3): p. 273–283.
 58. Zhang, J., et al., *Organic fertilizer application and Mg fertilizer promote banana yield and quality in an Udic Ferralsol*. PLoS One, 2020. **15**(3): p. e0230593.
 59. Mebrahtom, S., *Short Term Effect of Vermicompost on Soil Chemical Properties under Maize (*Zea mays* L.) Field in Northern Ethiopia*. Asian Soil Research Journal, 2024. **8**(1): p. 46–55.
 60. Kidanemariam, W., G. Agegnehu, and E. Molla, *The Ameliorative Effects of Lime and Vermicompost on Yield and Yield Components of Barley (*Hordeum vulgare* L.) and Soil Properties in Acidic Soil of Northwestern Ethiopia*. International Journal of Plant & Soil Science, 2025. **37**(2): p. 318–334.
 61. Workineh, M. and K. Kitila, *Effect of Integrated Application of Vermicompost and Inorganic Fertilizers on Yield and Yield Components of Bread Wheat in Adami Tulu Jido Kombolcha District of East Showa Zone, Ethiopia*. International Journal, 2024. **8**(3): p. 74–81.

62. Teka, K., et al., *Effect of vermicompost on soil fertility and crop productivity in the drylands of Ethiopia*. Compost Science & Utilization, 2024. **31**(3-4): p. 75–85.
63. Regasa, A., W. Haile, and G. Abera, *Effects of lime and vermicompost application on soil physicochemical properties and phosphorus availability in acidic soils*. Scientific Reports, 2025. **15**(1): p. 25544.
64. Raj, R., et al., *Effect of Vermicompost and Inorganic Fertilizer on Physico-Chemical Properties of Soil on Cowpea (Vigna unguiculata)*. Journal of Advances in Biology & Biotechnology, 2024. **27**(7): p. 1263–1269.
65. sheikhmous Othman, S. and M.N. Al-Khalaf, *The Effect of Different Types of vermicompost fertilizers in some Physical properties of the soil in Al-Hasaka Governorate*. The Libyan Journal of Agriculture, 2025. **30**(2): p. 34–54.
66. Sarhan, O. and H. Al-Alawy. *The Effect of Vermicompost and Mycorrhiza Fungi on some Soil Properties*. in *IOP Conference Series: Earth and Environmental Science*. 2025. IOP Publishing.
67. Parihar, S.S., et al., *Elucidating Potential Application of Vermicompost on Alluvial Soil (Entisols) Physico-chemical Properties of Gwalior District, Madhya Pradesh*. Madhya Pradesh.
68. Çirka, M., et al., *Effects of vermicompost applications on some yield and yield properties of wheat*. MAS Journal of Applied Sciences, 2022. **7**(1): p. 146–156.
69. Aslam, Z., et al., *Morpho-physiological, biochemical and yield responses of wheat (Triticum aestivum L.) to vermicompost, simple compost and NP fertilizer applications*. Pak. J. Bot, 2023. **55**(6): p. 2143–2154.
70. Hadis, M., G. Meteke, and W. Haile, *Response of bread wheat to integrated application of vermicompost and NPK fertilizers*. African Journal of Agricultural Research, 2018. **13**(1): p. 14–20.
71. Yitbarek, T., R. Redi, and S. Kibebew, *Enhancing Productivity of Bread Wheat (Triticum aestivum L.) Through Integrating Vermicompost and N fertilizer in Meskan, Central Ethiopia*. Jefore Ethiopian Journal of Applied Sciences, 2025. **1**(1): p. 52–64.
72. Fischer, R., *The importance of grain or kernel number in wheat: A reply to Sinclair and Jamieson*. Field Crops Research, 2008. **105**(1-2): p. 15–21.

73. Oyege, I. and M.S. Balaji Bhaskar, *Effects of vermicompost on soil and plant health and promoting sustainable agriculture*. Soil Systems, 2023. **7**(4): p. 101.
74. Singh, G., et al., *Effect of integrated nutrient management on nutrient uptake and grain yield of wheat (Triticum aestivum L.) under irrigated conditions*. Journal of Pharmacognosy and Phytochemistry, 2019. **8**(1): p. 1077–1080.
75. Basir, A., et al., *Integration of compost with mineral NPK fertilizers for improving wheat yield and soil health*. Pak. J. Bot, 2025. **57**(3): p. 981–989.
76. Yadav, A.K., et al., *Effect of FYM, Vermi-Compost, Azotobacter Inoculation and Chemical Fertilizers on Growth and Yield in Wheat (Triticum aestivum L.)*. International Journal of Environment and Climate Change, 2023. **13**(12): p. 1312–1316.
77. Arancon, N., et al., *Influences of vermicomposts on field strawberries: 1. Effects on growth and yields*. Bioresource technology, 2004. **93**(2): p. 145–153.
78. Gameda, F., et al., *Effect of integrated vermicompost and chemical nitrogen fertilizer for productivity of bread wheat (Triticum aestivum L.)*. Journal of Scientific Agriculture, 2024. **8**: p. 44–50.
79. Ahmad, M. and S. Tripathi, *Effect of integrated use of vermicompost, FYM and chemical fertilizers on soil properties and productivity of wheat (Triticum aestivum L.) in alluvial soil*. The Journal of Phytopharmacology, 2022. **11**(2): p. 101–106.
80. Karan, S., et al., *Amelioration of Vermicompost and Inorganic Fertilizer on Late-Sown Wheat Productivity*. International Journal of Environment and Climate Change, 2023. **13**(8): p. 2198–2207.
81. Gosa, R., et al., *Impact of Combined Vermicompost and Inorganic Fertilizers on Bread Wheat Yield, Yield Component and Soil Properties in Sinana District, Bale Highlands, Ethiopia*. Cross Current Int J Agri Vet Sci, 2025. **7**(1): p. 9–15.
82. Weldegebriel Gebrehiwot, T.B., Tsadik Tadele, Kinfe Tekulu, Geberesemaeti Kahsu, Solomon Mebrahtom, Samrawit Mebrahtu, Goitom Aregawi, Gidena Tasew, and Aklil Gebremedhin. , *Evaluation of different level of vermicompost on yield and yield components of wheat at vertisols of L/Machew District*. Asian Soil Research Journal, 2020.

83. Ebrahim, J., *Cost Effectiveness of Wheat Production Using Vermicompost and NPS Fertilizer at Mao Komo Districts, Western Ethiopia*. Innovation, 2025. **6**(1): p. 1–7.
84. Ali, N., et al., *Influence of different organic manures and their combinations on productivity and quality of bread wheat*. Journal of Soil Science and Plant Nutrition, 2020. **20**(4): p. 1949–1960.
85. Falconer, D.S., *Introduction to quantitative genetics*. 1996: Pearson Education India.