

Response of Vertisol and yield of bread wheat (*Triticum aestivum* L.) to short-term application of integrated soil fertility management practices

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Abstract

Purpose

*Soil fertility depletion is a serious problem in Ethiopia, and in turn, the actual yield of wheat is extremely low compared to the potential yield. Hence, a field experiment was conducted in the 2023–2024 main cropping season to determine the effects of the integrated use of vermicompost (VC) and inorganic fertilizer (IF) on some soil physicochemical properties and the yield of bread wheat (*Triticum aestivum* L.).*

Method

The experiment involved a combination of four levels of VC (0, 3, 6, and 9 t ha⁻¹) and three levels of combined IF (0%, 50%, and 100% of the recommended blended NPS and UREA). The experiment was set up in a randomized complete block design with three replications. All collected soil and agronomic data were analyzed using SAS software.

Result

Results claimed that the highest pH (6.77), available phosphorus (19.26 ppm), total nitrogen (0.27%), and CEC (29.77 cmolc kg⁻¹) were obtained from the integrated application of 6 t ha⁻¹ VC with 100% of the recommended IF and 9 t ha⁻¹ VC with 50% of the recommended IF. Moreover, the integrated application of 6 t ha⁻¹ VC with 50% of the recommended IF gave the highest bread wheat grain yield (4066.67 kg ha⁻¹) and maximum net benefit (167057.7 ETB).

Conclusion

Thus, it can be concluded that integrated application of 6 t ha⁻¹ VC and 50% of the recommended IF is the most recommended and economically feasible soil fertility management practice for improving soil fertility and, in turn, bread wheat yield.

1. Introduction

Wheat contributes to over 17% of the total grain production in Ethiopia (CSA, 2020). Ethiopia's actual wheat productivity is 3 t ha⁻¹ (CSA, 2021), which is lower than the world average productivity of 52 t ha⁻¹ (USDA, 2020). In general, the main reasons for the low-yield area are a lack of improved varieties, insufficient soil fertility, insect pests, and inefficient post-harvest handling (Adugnaw and Dagninet, 2020). Low soil fertility due to intensive crop cultivation, complete crop residue removal, and high nutrient depletion rates are some of the major causes of low wheat yield (Fanuel et al., 2018). According

to Kebede and Yamoah (2009), soil degradation and nutrient depletion are severe threats to agricultural productivity in Ethiopia. Annually, Ethiopian soils lose 122 kg ha^{-1} of nitrogen (N), 13 kg ha^{-1} of phosphorus (P), and 82 kg ha^{-1} of potassium (K). The annual rate of soil loss is higher than the rate of soil formation (Jemal, 2021). Removal of crop residue for livestock feeding and fuel, monocropping, and cultivation on steep slopes contribute to soil erosion (Yayeh et al., 2022). As a result, Ethiopia cannot meet its present needs with the amount of wheat produced (Yihenew, 2002; Minot et al., 2015). Furthermore, another factor contributing to Ethiopia's declining soil fertility is the inadequate application of both organic and inorganic fertilizers (Kraaijvanger and Veldkamp, 2015).

Sustainable agricultural productivity has not increased solely through the application of chemical fertilizers (Gete et al., 2010; Workineh et al., 2021). The excessive and ongoing use of inorganic fertilizers, especially nitrogen (N), can hasten the mineralization of organic elements, resulting in soil deterioration and ecological issues (Liu et al., 2010). Similarly, chemical fertilizers, even when applied sparingly, were unable to sustain high yield levels over time due to the degradation of the physical and biological habitats of the soil brought on by the low amount of organic matter in the soil (Javaria and Khan, 2010). Integrated soil fertility management (ISFM) is a collection of techniques used on smallholder farms to boost output and optimize input utilization. The combined use of cropping systems, inorganic, organic resources, and other amendments are all part of ISFM. It delivers soil and crop productivity gains, increased resilience, and mitigation benefits. One of the many ISFM techniques utilized globally is the combined application of organic and inorganic sources of soil fertility management techniques, such as VC and inorganic fertilizers (Vanlauwe et al., 2012). Vermicompost is organic material obtained from earthworms digesting waste and is a useful organic fertilizer for improving soil's physicochemical properties and, in turn, increasing crop production (Barlas et al., 2018). It has ammonium (NH_4^+) and nitrate (NO_3^-), which are plant-available forms of nitrogen (Kurovsky et al., 2021). The integrated use of VC with inorganic fertilizers increased soil organic matter and nutrient levels, which raised yields of bread wheat (Tolera and Tesfaye, 2021). Therefore, the objective of this study was to examine the short-term synergistic effects of the integrated use of VC and inorganic fertilizers on soil properties and, in turn, bread wheat yield.

2. Materials and Methods

2.1. Description of the Study Area

The study was underway in the *MekaneSelam* district in Northeast Ethiopia. It is located in the latitudes and longitudes of $10^\circ 45'00''\text{N}$ - $10^\circ 50'00''\text{N}$ and $38^\circ 45'00''\text{E}$ - $38^\circ 50'00''\text{E}$, respectively, with the altitude ranging from 1500 to 3893 m.a.s.l. (MDAO, 2023). The area is grouped under midland agroecology with the major soil type of vertisol, and the most dominant land use type is cultivated land (Nuru and Taminaw, 2021). The temperature ranges from 10°C to 30°C during the experimental year, while the average monthly rainfall varies between 5 mm and 310 mm. The rainfall distribution across the cropping seasons is described in Fig. 1. Among the months, the highest amount of rainfall occurred in July and

August. The dominant crops grown include bread wheat (*Triticum aestivum* L.), teff (*Eragrostis teff*), chickpea (*Cicer arietinum* L.), and sorghum (*Sorghum bicolor*) (MDAO, 2023).

To characterize the soil's physicochemical properties of the experimental site before the start of the experiment, composite soil samples were taken diagonally at five points from 0–20 cm soil depth. A core sampler was used to gather undisturbed samples to calculate the bulk density of the soil. These composited soil samples were again composited into one. After being gathered, the soil samples were labeled, bagged, and delivered to the Bahir Dar University soil & plant analysis laboratory center for physicochemical property preparation and analysis. In preparation for the analysis, it was allowed to air dry before being sieved through a 2mm sieve. To ascertain the amount of total nitrogen and soil organic carbon, soil samples were further sieved through a 0.5 mm screen. Using the conventional soil analysis protocols listed in Table 1, soil samples were examined for a few chosen criteria. According to the findings, the study site's soil texture belongs to the sand-clay loam class (Hazelton and Murphy, 2007). The soil is moderately acidic, with a pH of 5.9 (Hazelton and Murphy, 2007). In addition to having a very low amount of organic carbon (1.59%) (Landon, 1991), the soil also has low levels of accessible phosphorus (6.75 ppm) (Olsen et al., 1954) and total nitrogen (0.16%) (Landon, 1991). The other soil physicochemical characteristics of the experimental site are listed in Table 1 before the experiment begins.

Table 1

Methods of soil laboratory analysis and the resulting soil physicochemical properties of the experimental site before planting. BD = bulk density, pH = power of hydrogen, OC = organic carbon, OM = organic matter, TN = total nitrogen, and AvP = available phosphorus. CEC = cation exchange capacity; Exc.Ca = exchangeable calcium; Exc.Mg = exchangeable magnesium; Exc. K = exchangeable potassium; and Exc.Mg = exchangeable odium.

Soil parameter	Methods of soil analysis	Value	Rating	References
BD (gcm^{-3})	Core sampler method (Blake and Hartge, 1986)	1.25	Low	Hazelton and Murphy (2007)
Sand (%)		48	-	
Silt (%)		22	-	
Clay (%)		30	-	
Soil textural class	Hydrometer method (Birru, 1979)		Sand clay loam	Hazelton and Murphy (2007)
pH (H_2O)	Potentiometer pH meter (McLean, 1982)	5.95	Moderately acidic	Hazelton and Murphy (2007)
OC (%)	Wet digestion methods (Walkley and Black, 1934)	1.59	very low	Landon (1991)
TN (%)	Kjeldhal digestion, distillation, and titration methods (Bremner and Mulvaney, 1982)	0.16	Low	Landon (1991)
AvP. (ppm)	Olsen methods (Olsen et al., 1954)	6.75	Low	Olsen et al. (1954)
CEC ($\text{cmol}_c\text{kg}^{-1}$)	Ammonium acetate method (Chapman, 1965)	20.50	Medium	Landon (1991)
Exc.Ca ($\text{cmolc}(+)\text{kg}^{-1}$)	Atomic absorption spectrophotometer method, (Rowell, 1994)	10.8	High	FAO (2006)
Exc.Mg ($\text{cmolc}(+)\text{kg}^{-1}$)		2.77	Medium	
Exc.K ($\text{cmolc}(+)\text{kg}^{-1}$)	Flame photometer method (Rowell, 1994)	0.52	Medium	FAO (2006)
Exc.Na ($\text{cmolc}(+)\text{kg}^{-1}$)		0.23	Low	FAO (2006)

BD = bulk density, pH = power of hydrogen, OC = organic carbon, OM = organic matter, TN = total nitrogen, and AvP = available phosphorus. CEC = cation exchange capacity; Exc.Ca = exchangeable calcium; Exc.Mg = exchangeable magnesium; Exc. K = exchangeable potassium; and Exc.Mg = exchangeable odium.

2.2. Experimental Material

The wheat variety “*kekeba*” (pica flour) was used as a test crop. The selection criteria were the preference of farmers and characteristics of fast-growing with a maximum yield of 3.3–5.2 t ha⁻¹ (EARO, 2004). The variety was collected from the Adet Agriculture Research Centre (AARC). The fertilizer sources were blended NPS fertilizer (19-38-7), urea (46N), and well-decomposed vermicompost.

2.2.1. Experimental treatments, design, and procedures

The experimental treatments were three levels of combined inorganic fertilization (IF) (NPS and urea) (0%, 50%, and 100% of the recommended inorganic fertilizer) and four levels of vermicompost (VC) (0, 3, 6, and 9 t ha⁻¹). These treatments were organized according to a randomized complete block design (RCBD), with each treatment replicated three times. The recommended rates of NPS, UREA, and Seed rate for wheat production were 120, 100, and 150 kg ha⁻¹, respectively (Tolcha and Tolera, 2019). The gross & net plot sizes of each treatment were 3 m × 3 m (9 m²) and 2.80 m × 2.2 m (6.16 m²), respectively. The distances between the adjacent replications and plots were 1.5 m and 0.75 m, respectively. Land preparation was done using an oxen plow, where the fields were plowed three times, while disking and harrowing were done manually. Wheat was drilled in each plot with 20 cm row spacing. All the blended NPS fertilizer, half of the urea fertilizer, and a different rate of vermicompost were applied to each experimental unit at the time of sowing, while the remaining half of the urea fertilizer was applied at the tillering stage. Agronomic management practices were done following the local extension recommended packages.

2.3. Data Collection

2.3.1. Vermicompost (VC) nutrient analysis

To determine the chemical properties (Nutrient content), such as pH 1:2.5 (H₂O), organic carbon, organic matter, total nitrogen, available phosphorus, etc., of the VC, samples were subjected to the Bahir Dar University Soil and Plant Laboratory Analysis Centre. The standard methods and procedures of VC nutrient analysis are described in Section 2.1 and Table 1. The nutrient content of VC was 1.74% nitrogen, 127.84 ppm phosphorus, and 19.20 cmol kg⁻¹ potassium. The nutrient content of well-rotten VC ranges from 1.2% to 2.5% nitrogen, 0.9% to 1.7% phosphorus, and 1.5% to 2.5% potassium (Gupta et al., 2021). The other results of the chemical analysis of VC are described in Table 2.

Table 2
Chemical properties (Nutrient content) of the vermicompost

S/N	Vermicompost property	Unit	Value
1	pH1:2.5 (H ₂ O)		7.76
2	Organic carbon	%	12.43
3	Organic matter	%	21.43
4	Total nitrogen	%	1.74
5	Available phosphorus	Ppm	127.84
6	C: N ratio	-	7.14
7	Cation exchange capacity	cmol _c kg ⁻¹	47
8	Exchangeable calcium	cmol _c kg ⁻¹	25.5
9	Exchangeable magnesium	cmol _c kg ⁻¹	21.3
10	Exchangeable potassium	cmol _c kg ⁻¹	19.20
11	Exchangeable sodium	cmol _c kg ⁻¹	2.07

2.3.2. Treatment-wise post-harvesting soil sampling and analysis

After harvesting, treatment-wise soil samples were collected from each experimental plot. The method of soil sampling and laboratory analysis, and the analysis procedure, are similar to those of soil samples taken before planting, as described in section 2.1, Table 2.

2.3.3. Agronomic data collection

Plant height (cm) was measured from ground level to the top of the spike, excluding the awns of ten randomly taken plants from all harvestable rows of the plot, and recorded as the average height per plant. The total tiller per plant was from 1 m² to be reported as the number of tillers per m². The number of head-bearing tillers (effective tillers) was determined by counting the head-bearing tillers per m² in the net harvestable area at physiological maturity. The plants in the net plot area were harvested and sun-dried until a constant dry weight was attained. Dried plants were weighed to determine the biomass yield on a plot basis and converted into kg per hectare. Grain yield was measured by taking the weight of the grains threshed (after sun drying) from the net plot and converting it to kg per hectare after adjusting the grain moisture content to 12.5%. The moisture correction factor was calculated using the following formula (Bouyoucos, 1962):

$$\text{Adjusted Yield} = \frac{100 - \text{Measured moisture content } \%}{100 - 12.5\%}$$

Therefore, 12.5% moisture-adjusted grain yield = moisture correction factors x grain yield obtained from each plot.

2.4. Data Analysis

2.4.1. Statistical data analysis

All selected post-harvest soil and agronomic data from the experimental field were collected and entered into Microsoft Office Excel. The same software was used for data management. Data were subjected to analysis of variance (ANOVA) using statistical procedures as described by Gomez and Gomez (1984), with the General Linear Model (GLM) of the statistical analysis software (SAS, 2014), version 9.4. Before analysis, the data were checked for normal distribution following the scatter plot technique. When the analysis of variance showed significant differences among treatments at ($P < 0.05$) of probability, mean separation was conducted using the Duncan multiple range test (DMRT). Multiple linear regression analysis was conducted to determine the association between (i) Soil physiochemical and integrated soil fertility management (ISFM) and (ii) agronomic attributes and ISFM.

2.4.2. Partial budget analysis

The profitability of the integrated use of VC and IF was calculated using partial budget analysis following the International Maize and Wheat Improvement Center Manual (CIMMYT, 1988). Urea, NPS, VC, and labor requirements for fertilization were considered as inputs and variable costs. Other expenses were regarded as fixed costs, including cleaning, weeding, harvesting, land preparation, and rental fees. Yields of grain and straw were regarded as the outputs. The average cost for January through September of 2023 was used to compute all expenses during the experiment. The local costs of the yields of bread wheat and straw were 50 and 3 Ethiopian Bir (ETB) kg^{-1} , respectively. The local price of 40 ETB kg^{-1} for urea, 40.5 ETB kg^{-1} for NPS, and 4.5 ETB kg^{-1} for VC fertilizer. Transporting the VC fertilizer and the inorganic fertilizers (urea and NPS) costs 0.25 and 2.5 ETB kg^{-1} , respectively. The grain yield was adjusted downward by 10% to reduce the yield gap between experimental plots and farmers' fields.

Finally, total variable cost (TVC) was the total cost that varied for each treatment and was the sum of the individual costs that varied. The field price was multiplied by the adjusted yield to determine the gross benefit (GB) for each treatment. The total costs that varied were subtracted from the gross field benefits to determine the net benefit (NB). The marginal net benefit (i.e., the change in net benefits) was divided by the marginal cost (i.e., the change in expenses) to determine the marginal rate of return (MRR%), which was then expressed as a percentage.

3. Results and Discussion

3.1. Results

3.1.1. Residual effect of short-term ISFM on soil physicochemical properties

The analysis of variance (ANOVA) showed that bulk density (BD), soil pH, soil organic carbon (OC), total nitrogen (TN), available phosphorus (Ava. P), and cation exchange capacity (CEC) were significantly ($P < 0.05$) affected by the main effects of VC and inorganic fertilizers (IF) and by their interactions. On the other hand, the main effect of VC significantly ($P < 0.05$) affected the Ex. Ca and Na of the soil, but IF and the interaction effect between IF and VC showed a non-significant difference ($P > 0.05$) (Table 3). The minimum value of BD (1.04 g cm^{-3}) was obtained from the integrated application of 9 t ha^{-1} VC with 100% of the recommended IF, while the maximum amount of BD (1.21 g cm^{-3}) was obtained from the control plot (Table 3). The level of soil bulk density decreases with the integrated application of VC and IF since the VC in the combination enhances soil structure and serves as a source of nutrients that plants can use. The BD of the treatments treated with 9 t ha^{-1} VC and 100% of the recommended IF was 42% lower than the pre-sowing soil BD (Table 4).

The integrated application of 6 t ha^{-1} VC and 100% of the recommended IF resulted in the highest soil pH (6.77) (Table 3). Applying this ISFM increased the soil pH by 12.11% over the pH of the soil sampled before sowing (Table 4). Whereas the lowest soil pH (5.87) was obtained from the control plot. The increase in pH in this experimental plot was due to the release of pH from VC and the presence of root biomass in the soil. Multiple linear regression also clearly showed that the soil pH increased in line with the increase in both types of fertilizers (Table 5).

The integrated application of 9 t ha^{-1} VC with 50% of IF produced the highest soil organic carbon (2.84%), whereas the control plot produced the lowest (1.68%) (Table 3). Applying the former ISFM increased the soil organic carbon by 44% over the organic carbon of the soil sampled before sowing (Table 4). Improved organic matter decomposition led to higher soil organic matter levels, which in turn increased the organic carbon content as compared to the control. This is also described by multiple linear regression, that the soil organic carbon increased in line with the increase in both types of fertilizers (Table 5).

The maximum soil total nitrogen content (0.27%) was obtained from the integrated application of 9 t ha^{-1} VC with 100% of the combined use of the recommended IF (Table 3). Applying this ISFM increased the soil total nitrogen by 41% over the soil sampled before sowing (Table 4). Conversely, the minimum soil total nitrogen content (0.18%) was obtained from the control plot (Table 3). The content of total nitrogen increased by ISFM could be related to the addition of N that was released from VC through mineralization and IF. Total nitrogen increases as the amount of organic carbon in the soil increases as a result of the use of VC fertilizer. This is more described by the linear relationship between the integrated use of both types of fertilizers and total nitrogen, as explained by multiple linear regression (Table 5).

The maximum soil Av P. (19.26 ppm) was obtained from the integrated application of 6 t ha⁻¹ VC and 100% of the combined use of the recommended IF (Table 3). Applying this ISFM increased the soil Av P. by 65% over the soil sampled before sowing (Table 4). The lowest soil Ava P. (10.57 ppm) was obtained from the control plot. The increase in Ava P. from the ISFM could be due to the addition of phosphorus from VC and blended NPS fertilizer. The value of the Ava P. after crop harvest was higher than the Ava P. before planting due to the residual effect of the applied ISFM usage. Moreover, Multiple linear regression showed that Ava P. increased in line with the increase in both types of fertilizers (Table 5).

The maximum soil cation exchange capacity (29.77 cmolc kg⁻¹) was obtained from the integrated application of 9 t ha⁻¹ VC along with 100% of the combined use of the recommended IF, while the lowest soil CEC (21.00) was obtained from the control plot (Table 3). The largest CEC values of soil obtained from the above ISFM could be attributable to an increase in soil organic carbon content, which increases the total number of exchange sites and the release of essential nutrients from the VC for plant growth. Applying this ISFM increased the soil CEC by 31% over the soil sampled before sowing (Table 4). Moreover, multiple linear regression showed that soil cation exchange capacity increased in line with the increase in both types of fertilizers (Table 5).

The highest soil exchangeable calcium (13.47 cmolc kg⁻¹) was obtained from the combined utilization of 9 t ha⁻¹ VC with null inorganic fertilizer, while the minimum soil exchangeable calcium (10.87 cmolc kg⁻¹) was obtained from the control plot (Table 3). The concentration of Ca in VC and root biomass is what causes the increase in exchangeable Ca that results from the use of VC.

Table 3

The interaction effect of VC and inorganic fertilizer rate on selected soil properties after the harvesting of bread wheat

Treatment combination		Soil physicochemical properties						
VC	NPS+urea	BD	pH	OC	TN	AvP	CEC	Exc.Ca
0	0.00	1.21 ^a	5.87 ^d	1.68 ^e	0.18 ^e	10.57 ^f	21.00 ^d	10.82 ^d
	50.00	1.18 ^{abc}	6.06 ^{cd}	1.98 ^{de}	0.22 ^{cd}	13.88 ^e	26.07 ^{bc}	11.40 ^{cd}
	100.00	1.19 ^{ab}	5.97 ^{cd}	2.11 ^{cd}	0.24 ^{bc}	16.97 ^{a-d}	28.00 ^{abc}	11.67 ^{cd}
3	0.00	1.15 ^{bcd}	6.18 ^c	2.01 ^{cde}	0.2 ^{de}	13.46 ^e	25.07 ^c	11.82 ^{bcd}
	50.00	1.13 ^d	6.52 ^b	2.09 ^{cd}	0.23 ^{bc}	15.49 ^{cde}	27.80 ^{abc}	12.43 ^{abc}
	100.00	1.12 ^d	6.57 ^{ab}	2.23 ^{cd}	0.26 ^{ab}	17.3 ^{abc}	28.87 ^{ab}	12.87 ^{abc}
6	0.00	1.14 ^{cd}	6.57 ^{ab}	2.05 ^{cde}	0.23 ^{bc}	14.64 ^{de}	27.90 ^{abc}	12.19 ^{a-d}
	50.00	1.11 ^d	6.69 ^{ab}	2.41 ^{bc}	0.25 ^{a-c}	16.89 ^{a-d}	28.37 ^{abc}	12.87 ^{abc}
	100.00	1.12 ^d	6.77 ^a	2.66 ^{ab}	0.26 ^{ab}	19.26 ^a	28.19 ^{abc}	13.29 ^{ab}
9	0.00	1.11 ^d	6.54 ^b	2.18 ^{cd}	0.24 ^{bc}	15.65 ^{cde}	26.58 ^{abc}	13.47 ^a
	50.00	1.07 ^{ef}	6.64 ^{ab}	2.84 ^a	0.26 ^{ab}	16.67 ^{bcd}	28.67 ^{ab}	12.62 ^{abc}
	100.00	1.04 ^f	6.67 ^{ab}	2.76 ^{ab}	0.27 ^a	18.29 ^{ab}	29.77 ^a	12.74 ^{abc}
LSD (5%)		*	*	*	*	*	**	*
VC (5%)		*	*	*	*	*	*	*
IF (5%)		*	*	*	*	*	*	*
CV (%)		1.11	1.06	5.76	3.63	4.87	3.89	3.99

VC = Vermicompost (t ha^{-1}), NPS+urea = combined application of blended NPS and urea (% of the recommended rate), BD = bulk density (g cm^{-3}); MS = moisture content; pH = power of hydrogen (H_2O); OC = organic carbon (%); TN = total nitrogen (%); AvP = available phosphorus (ppm); and CEC = cation exchange capacity ($\text{cmol}_c \text{g}^{-1}$). Ca=Calcium ($\text{cmol}_c \text{kg}^{-1}$). Mean values within a column followed by the same letter (s) are not significantly different from each other at the 5% probability level.

Table 4
Effect of ISFM on the post-harvest soil physicochemical properties

Soil parameter	Value		Change (%)
	Post harvest	Pre-sowing	
BD (gcm^{-3})	1.04	1.25	-20.19
pH (H ₂ O)	6.77	5.95	12.11
OC (%)	2.84	1.59	44.01
TN (%)	0.27	0.16	40.74
AvP. (ppm)	19.26	6.75	64.95
CEC (cmolckg^{-1})	29.77	20.5	31.14
Exc.Ca ($\text{cmolc}(+)\text{kg}^{-1}$)	13.47	10.8	19.82
Exc.Mg ($\text{cmolc}(+)\text{kg}^{-1}$)	3.4	2.77	18.53
Exc.K ($\text{cmolc}(+)\text{kg}^{-1}$)	0.67	0.52	22.39
Exc.Na ($\text{cmolc}(+) \text{kg}^{-1}$)	0.4	0.25	37.50

Table 5
Multiple linear regression between the interaction between VC (X1) and IF (X2) and soil physicochemical properties (Y).

Soil properties	Regression parameters						R ² (%)
	Intercept		Regression coefficient & probability level				
	Value (α)	Pvalue	Value (β1)	Pvalue	Value (β2)	Pvalue	
BD (g cm-3)	1.200	< .0001	-0.012	0.0001	-0.0003	0.049	86
pH	6.054	< .0001	0.067	0.0034	0.0016	0.2632	68
OC (%)	1.678	< .0001	0.076	0.0004	0.0046	0.0024	85
TN (%)	0.199	< .0001	0.004	0.0002	0.0004	< .0001	92
AvP	12.741	< .0001	0.284	0.0015	0.0383	< .0001	90
CEC (cmolc g-1)	25.328	< .0001	0.218	0.0191	0.0249	0.0033	73

In the multiple linear regression analysis, soil physicochemical properties were taken as a response variable (Y), and VC (X1) and IF (X2) were taken as explanatory variables. R² is the Coefficient of determination.

The maximum soil Mg ($4.1 \text{ cmolc kg}^{-1}$) was obtained from the application of 9 t ha^{-1} VC, while the lowest soil Mg ($2.85 \text{ cmolc kg}^{-1}$) was obtained from the control (Table 4). Soil exchangeable magnesium levels raised with the VC rate might be due to the maximum magnesium content of VC. Therefore, upon treatment, the majority of the treatments applied to the experimental site's soil indicated a moderate level of magnesium, while the maximum application of VC indicated a high level of Mg.

The maximum soil Mg ($4.1 \text{ cmolc kg}^{-1}$) was obtained from the application of 9 t ha^{-1} VC, while the lowest soil Mg ($2.85 \text{ cmolc kg}^{-1}$) was obtained from the control (Fig. 2). Soil exchangeable magnesium levels increased in line with the VC rate might be due to the maximum magnesium content of VC.

The maximum soil Na ($0.4 \text{ cmolc kg}^{-1}$) was obtained from applying 9 t ha^{-1} VC, while the lowest soil Na ($0.28 \text{ cmolc kg}^{-1}$) was obtained from the control plot (Fig. 2). The increase in soil exchangeable sodium level with the rise in the application rate of VC might be due to the maximum sodium content of VC.

3.1.2. Yield components and yield of bread wheat

The analysis of variance showed that the individual effects of VC and IF and their interaction significantly ($P < 0.05$) affect all the agronomic attributes (Table 6). The combination of 6 t ha^{-1} VC and 50% of the combined use of the recommended IF generated the largest number of seeds per spike (49.8), followed by 9 t ha^{-1} VC and 100% of the combined use of the recommended IF (48.67), while the lowest number of seeds per spike was obtained from the control treatment (30.33). This might be because inorganic fertilizers may supply plants with readily available nutrients during the early phases of growth, while organic fertilizers (VC) may increase the yield and yield components of bread wheat during the latter stages of growth.

The integrated use of 6 t ha^{-1} VC and 50% of the combined use of the recommended IF produced the highest effective tillers m^{-2} (426.33 m^2), while the control plot produced the lowest effective tillers (292.67 m^2) (Table 6). The role of N in increasing plant vegetative growth and the rapid conversion of synthesized carbohydrates into protein, increasing the number and size of growing cells, and, ultimately, an increase in the number of tillers could be the reason for the highest number of tillers at the highest rate of the above ISFM practices. Multiple linear regression showed that the number of effective tillers (m^{-2}) significantly increased in line with the increase in both types of fertilizers (Table 7).

The combined use of 9 t ha^{-1} VC and 100% of the combined use of the recommended IF produced the highest biomass yield (12900 kg ha^{-1}), while the control plot produced the lowest biomass yield ($7166.67 \text{ kg ha}^{-1}$) (Table 6). Increased IF and VC fertilizer rates could increase dry biomass production because nitrogen, phosphorus, and sulfur nutrients play a role in important plant functions and contribute to crop growth. The increase in biological yield with increased N rates might be due to enough nitrogen in the soil, encouraging vegetative wheat plant growth.

The combination of 6 t ha⁻¹ VC and 50% of the combined use of the recommended IF produced the highest grain yield (4066.67 kg ha⁻¹), while the control produced the lowest grain yield of bread wheat (1900 kg ha⁻¹) (Table 6). The highest grain yield at this combined application of VC and inorganic fertilizer might be related to the utilization of VC, which indirectly affects the physical conditions of the soil by improving water infiltration rates, enhancing plant root aeration, increasing soil water retention capacity, and reducing soil erosion. It is also favorable to soil microorganisms and promotes N, P, and K exchange, all of which improve plant growth. Multiple linear regression also confirmed that the number of effective tillers (m⁻²) significantly increased in line with the increase in both types of fertilizers (Table 7).

The integrated use of 6 t ha⁻¹ of VC and 50% of the recommended IF produced the maximum harvest index (40.43%), while the control plot produced the lowest harvest index (26.4%) (Table 6). The increased harvest index with the combined application of the above ISFM practice could be attributed to increased photo assimilation and subsequent separation into grains instead of straw, leading to a correspondingly bigger yield of grains than of vegetative biomass.

The combined use of 6 t ha⁻¹ VC with 50% of the combined use of the recommended IF produced the highest thousand seed weight (52.67 g), while the control plot produced the lowest thousand seed weight (42.00 g) (Table 6). This may have been caused by the combined application of fertilizers' greater nutritional concentrations. This might be because the quantity of panicles contributes more to the crop's final production than panicle weight.

Table 6

The interaction effects of VC and (combined use of inorganic fertilizer (NPS and urea) on the yield component of bread wheat

Treatment combination		Agronomic Attributes					
VC	NPS+urea	NSPS	NET	BY	GY	HI	TSW
0	0.00	30.33 ^b	292.67 ^c	7166.67 ^d	1900 ^d	26.40 ^b	42.00 ^c
	50.00	40.67 ^{ab}	372.67 ^{ab}	9600.00 ^c	2900 ^{bcd}	29.79 ^{ab}	44.33 ^{bc}
	100.00	46.7 ^a	385.33 ^{ab}	9966.67 ^{bc}	3433.33 ^{abc}	34.04 ^{ab}	49.33 ^{abc}
3	0.00	39.33 ^{ab}	331.33 ^{bc}	8333.33 ^{cd}	2783.33 ^{cd}	32.86 ^{ab}	44.00 ^{bc}
	50.00	44.27 ^a	383.33 ^{ab}	8833.33 ^{cd}	3366.67 ^{abc}	37.64 ^{ab}	47.00 ^{abc}
	100.00	48.4 ^a	393.67 ^{ab}	10233.33 ^{bc}	3533.33 ^{abc}	34.19 ^{ab}	49.33 ^{abc}
6	0.00	43.07 ^a	369.33 ^{ab}	9266.67 ^c	3200 ^{ab^c}	34.44 ^{ab}	45.33 ^{abc}
	50.00	49.8 ^a	426.33 ^a	10066.67 ^{bc}	4066.67 ^a	40.43 ^a	52.67 ^a
	100.00	45.47 ^a	392.00 ^{ab}	10200.00 ^{bc}	3550 ^{abc}	34.67 ^{ab}	47.00 ^{abc}
9	0.00	46.0 ^a	398.33 ^{ab}	9666.67 ^{bc}	3600 ^{abc}	37.32 ^{ab}	47.67 ^{abc}
	50.00	47.1 ^a	402.33 ^a	11666.67 ^{ab}	3800 ^{abc}	33.03 ^{ab}	50.00 ^{ab}
	100.00	48.67 ^a	417.33 ^a	12900 ^a	3933.33 ^{ab}	30.71 ^{ab}	50.67 ^{ab}
LSD (5%)		*	*	*	*	*	*
VC (5%)		*	*	*	*	*	*
IF (5%)		*	*	*	*	*	*
CV(%)		7.64	5.78	6.43	9.90	10.90	5.04

VC = Vermicompost (t ha^{-1}), NPS+urea = combined application of blended NPS and urea (% of the recommended rate), NSPS = number of seeds per spike; NET = number of effective tillers m^{-2} ; BY = Biomass yield (kg ha^{-1}); GY = grain yield (kg ha^{-1}), HI = harvest index (%), TSW = thousand seed weight (gram). Mean values within a column followed by the same letter (s) are not significantly different from each other at the 5% probability level.

Table 7

Multiple linear regression between the interaction between VC (X1) and IF (X2), and the Agronomic attributes (Y).

Agronomic attribute	Regression parameters						R ² (%)
	Intercept		Regression coefficient & Probability level				
	Value (̑)	Pvalue	Value (̒1)	Pvalue	Value (̒2)	Pvalue	
Number of seeds per spike	39.83	< .0001	0.557	0.048	0.052	0.04	60
Number of effective tillers	347.30	< .0001	4.707	0.038	0.340	0.08	57
Biomass yield (t ha-1)	7642.35	< .0001	256.928	0.0082	21.184	0.01	76
Thousand kernel weights (g)	44.10	< .0001	0.419	0.0959	0.035	0.12	46
Grain Yield (kg ha-1)	2777.25	< .0001	87.843	0.0089	4.963	0.06	70

In the multiple linear regression analysis, agronomic attributes were taken as a response variable (Y), and VC (X1) and IF (X2) were taken as explanatory variables. R² is the Coefficient of determination.

3.1.3. Partial budget analysis

The partial budget analysis result revealed a maximum net benefit of 167057.7 ETB ha⁻¹, with an acceptable MRR of 965.75% observed at the application of 6 t ha⁻¹ VC and 50% of the combined use of the recommended IF (Table 8). The combined application of optimal organic and inorganic fertilizers is vital for improving the sustainability of soil fertility and crop productivity, and profitability.

Table 8
Partial budget analysis of vermicompost and inorganic fertilizer (NPS and urea) applications

VC	NPS+urea	ASY	AGY	TVC	GI	NBT	MRR
0.00	0.00	4740.00	1710.00	0.00	99720.00	99720.00	0
	50.00	6030.00	2610.00	3642.50	148590.00	144947.50	1241.66
	100.00	4995.00	2505.00	7285.00	140235.00	164855.30	546.54
3.00	0.00	5880.00	3090.00	14250.00	172140.00	125985.30	D
	50.00	4920.00	3030.00	17892.50	166260.00	148367.50	614.47
	100.00	5460.00	2880.00	21535.00	160380.00	155555.30	197.33
6.00	0.00	6030.00	3180.00	28500.00	177090.00	131880.00	D
	50.00	5400.00	3660.00	32142.50	199200.00	167057.70	965.75
	100.00	5460.00	3240.00	35785.00	178380.00	141920.00	D
9.00	0.00	5985.00	3195.00	42750.00	177705.00	135630.00	D
	50.00	7080.00	3420.00	46392.50	192240.00	145847.50	280.50
	100.00	8070.00	3540.00	50035.00	201210.00	151175.30	146.26

VC = Vermicompost (t ha^{-1}), NPS+urea = combined application of blended NPS and urea (% of the recommended rate), ASY=Adjusted straw yield (Kg ha^{-1}), AGY=Adjusted grain yield (Kg ha^{-1}), TVC = total variable cost (ETB), GI = gross income (ETB), NBT = net benefit (ETB), MRR= marginal rate of return (%), and ETB = Ethiopian birr.

3.2. Discussion

3.2.1. Residual effect of short-term ISFM on soil physicochemical properties

The BD of the treatments treated with 9 t ha^{-1} VC and 100% of the recommended IF was 42% lower than the pre-sowing soil BD (Table 4). Similar to this finding, Tolera and Tesfaye (2021) and Workineh et al. (2021) declared that the BD treated with VC and blended NPS fertilizer showed the lowest BD compared to the control treatment (Table 3). Getachew et al. (2016) and Widowati et al. (2020) also reported that using organic fertilizers (compost, manure, and biochar) decreased soil BD by increasing soil organic matter, porosity, and available water content.

Multiple linear regression also clearly showed that the soil pH increased in line with the increase in both types of fertilizers (Table 5). This result was supported by Kasahun and Mekonnen (2023), who stated that the combined use of 100% of the recommended IF with 8 t ha^{-1} of VC resulted in a maximum soil

pH of 6.69. Similarly, Tamado and Mitiku (2017) and Iqbal et al. (2021) reported that the pH of the soil was significantly raised in cereal cultivation with the integrated use of organic and inorganic fertilizer, whereas a single application of inorganic fertilizer lowered the pH of the soil.

This is also described by multiple linear regression, that the soil organic carbon increased in line with the increase in both types of fertilizers (Table 5). In agreement with the results of this study, Song et al. (2024) showed that a combination of chemical fertilizer and compost application produced the greatest amount of soil organic carbon OC (1.19%). Tamado and Mitiku (2017) also showed a significant rise in soil OC after the application of organic and inorganic fertilizers to food barley. Ahmed et al. (2022) reported the important impact of applying organic fertilizers either by themselves or in combination with inorganic fertilizers for adequate nutrient uptake and soil fertility maintenance and production.

Total nitrogen increases as the amount of organic carbon in the soil increases as a result of the use of VC fertilizer. This is more described by the linear relationship between the integrated use of both types of fertilizers and total nitrogen, as explained by multiple linear regression (Table 5). The result was consistent with the works of Habtamu et al. (2023), who stated that the plots treated with a combined application of 2.84 t ha^{-1} VC with 50% recommended NPS and urea fertilizers had the greatest TN (0.44%). The combination of VC with mineral N produced more total nitrogen than the control and 100% mineral nitrogen, as reported by Johannes et al. (2017).

The value of the Ava P. after crop harvest was higher than the Ava P. before planting due to the residual effect of the applied ISFM usage. Moreover, Multiple linear regression showed that Ava P. increased in line with the increase in both types of fertilizers (Table 5). The finding was supported by the works of Tolera and Tesfaye (2021), who showed that the highest Ava P. (23.49 ppm) was achieved from 15 t ha^{-1} VC + 100 kg ha^{-1} NPS fertilizer, whereas the lowest (9.22 ppm) was obtained from the control. The result was also consistent with the finding of Mekonnen et al. (2020), who reported that applying 2.84 t ha^{-1} VC with 50% recommended NPS and urea fertilizers produced the greatest Ava P. (35.44 mg kg^{-1}), but the lowest AvP (14.69 mg/kg) was obtained from control plots.

The largest CEC values of soil obtained from the above ISFM could be attributable to an increase in soil organic carbon content, which increases the total number of exchange sites and the release of essential nutrients from the VC for plant growth. This result is in line with studies by Mekonnen et al. (2020), who discovered that the control plot had the lowest CEC of $22.66 \text{ cmolc (+) kg}^{-1}$, while plots treated with a combined application of 2.84 t ha^{-1} VC with 50% recommended NPS + urea fertilizers had the greatest CEC of $34.36 \text{ cmolc (+) kg}^{-1}$. Similarly, Tolera and Tesfaye (2021) discovered that the control treatment produced the lowest CEC value ($22.20 \text{ cmolc kg}^{-1}$), whereas 15 t ha^{-1} VC + 100 kg ha^{-1} NPS fertilizer produced the highest CEC value ($25.23 \text{ cmolc kg}^{-1}$).

The concentration of Ca in VC and root biomass is what causes the increase in exchangeable Ca that results from the use of VC. The combined application of 7.5 t ha^{-1} VC and 75% NP improved the exchangeable Ca, Mg, K, CEC, organic carbon, total N, and available P by 341.51, 78.71, 133.3, 26.18, 33,

54.28, and 172.38%, respectively, in comparison to the control, according to Kibinesh and Isreal (2023). Additionally, Workineh et al. (2021) found that the combination of inorganic and organic fertilizers greatly increased the amount of exchangeable calcium in the soil.

Soil exchangeable magnesium levels raised with the VC rate might be due to the maximum magnesium content of VC. According to FAO (2006), exchangeable magnesium has a rating of $< 0.3 \text{ cmolc kg}^{-1}$ for very low, 0.3-1.0 for low, 1–3 for moderate, 3–8 for high, and > 8 for very high. Therefore, upon treatment, the majority of the treatments applied to the experimental site's soil indicated a moderate level of magnesium, while the maximum application of VC indicated a high level of Mg. The result was in line with that of McClintock and Diop (2005), who reported that the addition of compost raised the soil's CEC, exchangeable bases (Ca, Mg, and K), and organic matter content. Kumar et al. (2018) also stated that the application of VC significantly increased the concentration of exchangeable magnesium in the soil.

Soil exchangeable magnesium levels raised in line with the VC rate might be due to the maximum magnesium content of VC. According to FAO (2006), exchangeable magnesium has a rating of $< 0.3 \text{ cmolc kg}^{-1}$ for very low, 0.3-1.0 for low, 1–3 for moderate, 3–8 for high, and > 8 for very high. Therefore, upon treatment, the majority of the treatments applied to the experimental site's soil indicated a moderate level of magnesium, while the maximum application of VC indicated a high level of Mg. The outcome was consistent with the findings of McClintock and Diop (2005), who found that the addition of compost increased the soil's organic matter content, exchangeable bases (Ca, Mg, and K), and CEC. According to Kumar et al. (2018), the application of VC considerably raised the amount of exchangeable magnesium in the soil.

The increase in soil exchangeable sodium level with the rise in the application rate of VC might be due to the maximum sodium content of VC. On the contrary, Workineh et al. (2021) also reported that the interaction impact of organic and inorganic fertilizer rates on soil exchangeable Na concentrations after harvest was not significant.

3.2.1. Yield components and yield of bread wheat

This might be because inorganic fertilizers may supply plants with readily available nutrients during the early phases of growth, while organic fertilizers (VC) may increase the yield and yield components of bread wheat during the latter stages of growth. In agreement with this, Almaz and Kasa (2018) reported that a larger number of seeds per spike (46) of bread wheat was obtained from the combined application of the recommended N and P inorganic fertilizer and the 33:33:33% recommended rate of VC, compost, and inorganic fertilizer, respectively. Tariku et al. (2018) also reported the number of kernel seeds per plant increased when alone and integrated nutrient management techniques were applied as compared to non-fertilized fields.

The role of N in increasing plant vegetative growth and the rapid conversion of synthesized carbohydrates into protein, increasing the number and size of growing cells, and, ultimately, an increase in the number of tillers could be the reason for the highest number of tillers at the highest rate of the

above ISFM practices. The result was consistent with the works of Woubshet et al. (2017), who showed that the combination of lime and other organic and inorganic fertilizers may have had an advantageous impact, increasing the availability of NPK and resulting in a larger number of effective tillers. Similarly, Mitik and Legesse (2014) observed that the largest number of productive tillers m^{-2} and the highest number of grains per spike were achieved with the application of 5 t ha^{-1} farmyard manure combined with 75% of the recommended NP fertilizer.

Increased IF and VC fertilizer rates could increase dry biomass production because nitrogen, phosphorus, and sulfur nutrients play a role in important plant functions and contribute to crop growth. The increase in biological yield with increased N rates might be due to enough nitrogen in the soil, encouraging vegetative wheat plant growth. The finding was similar to the result of Gedefa and Dagne (2022), who claimed combinations of 1.5 t ha^{-1} VC with 200 kg ha^{-1} NPS produced significantly higher biomass production of bread wheat (14944 kg ha^{-1}). Tolera et al. (2018) stated that the combined use of 50:50 VC and conventional compost with recommended NP resulted in significantly the highest economic and biological yield of barley. Almaz and Kasa (2018) also reported that the biomass production of bread wheat increased significantly with the integrated application of both organic and inorganic fertilizers.

The highest grain yield at this combined application of VC and inorganic fertilizer might be related to the utilization of VC, which indirectly affects the physical conditions of the soil by improving water infiltration rates, enhancing plant root aeration, increasing soil water retention capacity, and reducing soil erosion. It is also favorable to soil microorganisms and promotes N, P, and K exchange, all of which improve plant growth. Multiple linear regression also confirmed that the number of effective tillers (m^{-2}) significantly increased in line with the increase in both types of fertilizers (Table 7). Kitila and Workina (2023) also demonstrated that the maximum grain yield (5130 kg ha^{-1}) was obtained from 50% of the recommended NP combined with 8 t ha^{-1} VC, while the lowest grain yield was recorded from the control treatment (1944 kg ha^{-1}). Gedefa and Dagne (2022) stated that the combination of 3 t ha^{-1} VC with 200 kg ha^{-1} NPS and 92 kg ha^{-1} N ($5722.2 \text{ kg ha}^{-1}$) and the control plot (750.0 kg ha^{-1}) had the highest and lowest bread wheat grain yield, respectively. Tolera and Tesfaye (2021) reported that a maximum grain yield of 7.36 t ha^{-1} was obtained from 5 t ha^{-1} VC + 50 kg ha^{-1} NPS fertilizer, and the minimum grain yield (2.94 t ha^{-1}) was obtained from the control plot.

The increased harvest index with the combined application of the above ISFM practice could be attributed to increased photo assimilation and subsequent separation into grains instead of straw, leading to a correspondingly bigger yield of grains than of vegetative biomass. The result is in line with the works of Aslam et al. (2019), who stated that the maximum harvest index (41.32%) was recorded when N:P: K 100:50:50 kg ha^{-1} + 10 t ha^{-1} cow dung VC was treated, followed by N:P: K 100:50:50 kg ha^{-1} + 10 t ha^{-1} paper waste VC. Similarly, Jemal (2022) stated that the combination of 10 t ha^{-1} VC and 100 kg ha^{-1} NPS produced the maximum harvest index (47.52%).

This may have been caused by the combined application of fertilizers' greater nutritional concentrations. This might be because the quantity of panicles contributes more to the crop's final production than panicle weight. Similar to this result, Girma et al. (2020) found that the application of 50% VC and 50% of the combined use of the recommended N and P resulted in the highest barley grain production of 4277 kg ha⁻¹ and a thousand grain weight. The integrated application of organic and inorganic fertilizers increased the weight of a thousand seeds from 10 g to 44 g (Woubshet et al., 2017).

3.3. Partial budget analysis

The combined application of optimal organic and inorganic fertilizers is vital for improving the sustainability of soil fertility and crop productivity, and profitability. This finding is in line with the findings of Kasahun and Mekonnen (2023), who reported that the combined application of 2.82 t ha⁻¹ of VC and 50% of the recommended inorganic NP fertilizer resulted in the maximum net benefit.

5. Conclusion

In comparison to the individual and null soil fertility management approach, the combined use of vermicompost and inorganic fertilizer significantly enhanced most soil chemical properties, as well as bread wheat agronomic attributes. More significantly, soil pH and AV. Phosphorus rose by 13.3% and 45.12%, respectively, when 6 t ha⁻¹ of vermicompost (VC) and 100% of the combined recommended inorganic fertilizer (IF) (NPS and urea) were applied together. Total nitrogen and cation exchange capacity were enhanced by 33%. 33% and 29. 46%, respectively, when 9 t ha⁻¹ of VC and 100% of the combined recommended IF were applied together. Furthermore, the combined application of 50% IF and 6 t ha⁻¹ VC enhanced grain yield by 53. 28% in comparison to the control. Applying 6 t ha⁻¹ of VC along with 50% of the combined recommended IF produced the highest net benefit (167057.7), and the marginal rate of return is 965. 75%) from an economic perspective. In conclusion, the most effective way to enhance soil fertility and, consequently, boost wheat production and the profitability of farmers in the study area and comparable agroecology is to apply 6 t ha⁻¹ of VC in combination with 50% of the recommended IF rates. Since the experiment was only carried out for one season and one area, this study ought to be repeated over time and place.

Declarations

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Ethics and Consent to Participate: The plant material, bread wheat (*Triticum aestivum* L.), was collected from cultivated sources in compliance with Ethiopia's national and institutional agricultural research regulations. The collection and use of plant material followed applicable local and national legislation,

and no protected or endangered plant species were used in the study. All plant resources were collected from sustainably farmed areas.

Consent to Publish: All authors have reviewed and authorized the final article and agree to its publication. The writers affirm that the information supplied is original and accurate.

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Figures

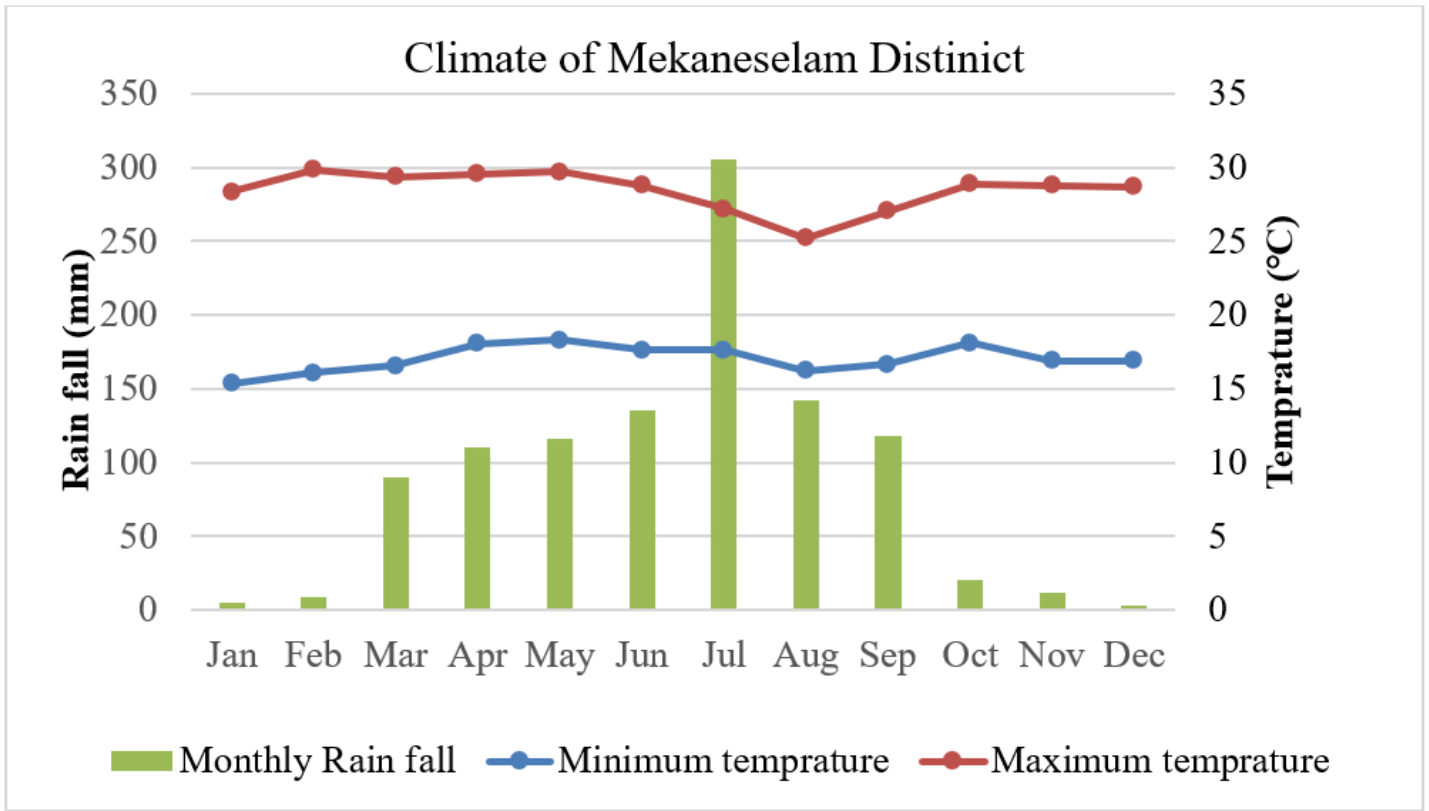


Figure 1

Monthly rainfall and temperature distributions in the study area during the experimental year (2023).

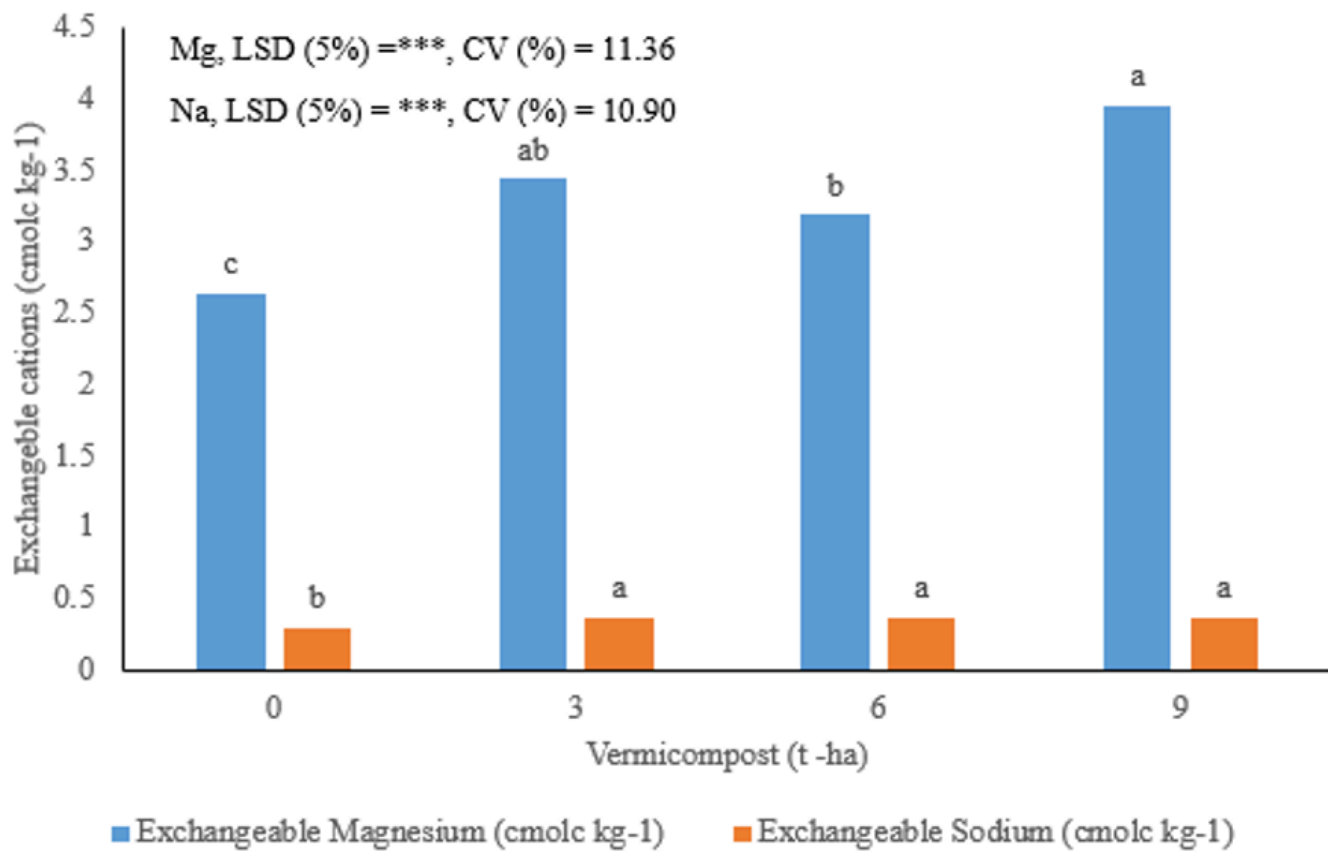


Figure 2

Effect of vermicompost on wheat post-harvest soil exchangeable Mg and Na. Mean values followed by the same letter (s) in the figure are not significantly different from each other at the 5% probability level.