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Wheat yield and soil physicochemical properties through mineral nitrogen and vermicompost application in Lasta district, North Ethiopia

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Ethiopia's soils are losing essential nutrients and organic matter, causing a drop in agricultural output. This experiment was therefore conducted to evaluate the effect of combining mineral nitrogen (N) and vermicompost (VC) on bread wheat yield and soil physicochemical properties in the Lasta district. During the 2023 cropping season, the trial employed a factorial design with varying levels of N (0%, 50%, 75%, and 100% of recommended) and VC (0%, 50%, and 100% equivalent to N) on a farmer's field. The soil samples were analyzed before and after treatment, and the data were analyzed using R software. The results indicated that the total N (TN) (0.131 ± 0.01%) and available phosphorus (Av. P) (22.97 ± 0.05) were recorded from 100% VC, the highest organic carbon (OC) (1.79 ± 0.01%) and CEC (36.8 ± 1.0 cmol+/kg) of the soil were recorded for the combined N and VC application, whereas the lowest TN (0.107 ± 0.01%) Av. P (19.17 ± 0.21), OC (1.05 ± 0.01) and CEC (23.37 ± 1.26) were recorded from the control. The highest grain (3955.33 ± 49.22 kg ha^{-1}) and biomass (9.30 ± 0.1 t ha^{-1}) yields were obtained with full N and VC application, while the lowest were observed in the control. Economic analysis revealed that applying fully recommended N with 100% VC as the N equivalent led to the highest net profit (290088.91 ETB) and acceptable marginal rate of return (1491.24%). It is recommended that farmers adopt 100% of the recommended N with 100% VC equivalence for optimal yields. Further research across diverse locations and years is suggested to validate and understand the residual effects on soil and yield improvements.

Keywords Integration, Nitrogen equivalence, Mineral nitrogen, Wheat yield, Vermicompost

Soil degradation is the most significant biophysical factor that causes a decrease in soil fertility and quality and limits crop production in Ethiopia[1]. As a result, the soils of the country are losing essential nutrients due to extensive cultivation, erosion, and residue removal[2]. Well-managed soils have more organic matter, nitrogen, and phosphorus than unmanaged soils. This increase in organic carbon enhances soil quality, particularly by increasing the nitrogen content[3,4].

The total wheat grain production in Ethiopia is 17%, making it the third most important cereal crop after tef (*Eragrostis tef*) and maize (*Zea mays L.*). Wheat cultivation in Ethiopia is expanding, covering approximately 1.89 million hectares, primarily due to government emphasis and rising prices. However, compared to the regional (2.8 t ha^{-1}) and national (3.1 t ha^{-1}) averages, North Wollo's wheat productivity, particularly in Lastadistrict, is significantly lower at 2.3 t ha^{-1}[5]. Several factors contribute to this low yield. Foremost among them is poor soil fertility, especially nitrogen deficiency[6]. In addition, studies by Zelleke et al.[1] highlight problems such as continuous mono-cultivation, improper land use practices, nutrient depletion (often referred to as nutrient mining), and inadequate fertilizer application. Other challenges associated with low wheat yield include climate change-induced stress and low adoption of technology[7–9] and limited investment[9].

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The addition of VC enhances overall soil properties, improves crop yield and sustains agricultural practices[10]. Likewise, several studies have reported that VC significantly improves both the yield and quality of wheat[11–14]. In addition, research by Ali et al.[15], Belete et al.[16] and Giday[17] concluded that increasing nitrogen application improved wheat grain yield.

However, the addition of inorganic fertilizer alone is insufficient to maintain adequate nutrient levels in the soil. According to Shibabaw et al.[18], the efficacy of NP fertilizers in soil organic matter-rich areas promotes higher crop yields and responsiveness to application. To address these problems[19], stressed the necessity of integrated nutrient management, combining organic and inorganic nutrients for sustainable and profitable farming. Co-application of chemical and organic fertilizers via a balanced approach is crucial for maximizing crop yield and preserving soil fertility. The application of 50% VC and 50% N fertilizer application increased rice crop yield[21]. Similarly, Agegnehu et al.[21] suggested that using 50% compost with half of the recommended mineral fertilizer rate is an effective alternative. Furthermore, Chimdessa and Sori[22] demonstrated that using VC with inorganic fertilizer enhances wheat yield and soil chemical properties. Additionally, VC application improves soil physicochemical properties and nutrient availability[23],[24].

The soil in the area has low nitrogen content, primarily due to depleted organic matter, complete removal of crop residues, and soil erosion. According toTilahun and Workat[25], the nitrogen level in the soil of the Lasta district is crucial, so it limits wheat yield in this district. Soil nutrient depletion for a long time leads to applying more nutrients for restoring soil fertility. However, the cost of mineral fertilizers has increased rapidly by more than 175%, causing a decline in wheat production and becoming a problem of good governance between the government and farmers. The sole application of inorganic fertilizers is not practical in the district due to high price, limited improvement in soil health and less responsive to the crop[26]. On the other hand, single applications of organic fertilizers are impractical due to the large quantity of materials needed, shortage of biomass, and high labor costs[1,27,28]. Farmers also lack expertise in VC and co-application of organic and inorganic fertilizer for improving soil fertility. There is a research gap in understanding how combining VC and N mineral fertilizers enhances soil fertility and crop productivity. Therefore, this study aimed to (i) evaluate the effects of VC and nitrogen fertilizers on selected soil physicochemical properties, (ii) assess their impact on wheat yield, and (iii) determine the economic viability of these integrated fertilizer management strategies.

Materials and methods

Description of the study areas

The experiment was conducted in Medagie kebele, Lasta district, which is located in the North Wollo zone of the Amhara regional state in North Ethiopia (Fig. 1). Based on 31 years of data (1993–2023), the Lasta-Lalibela districts have an annual rainfall of approximately 884.5 mm and mean minimum and maximum temperatures of 13.4 and 24.8 °C, respectively. During the cropping season, the annual rainfall was 636.9 mm (Kombolcha

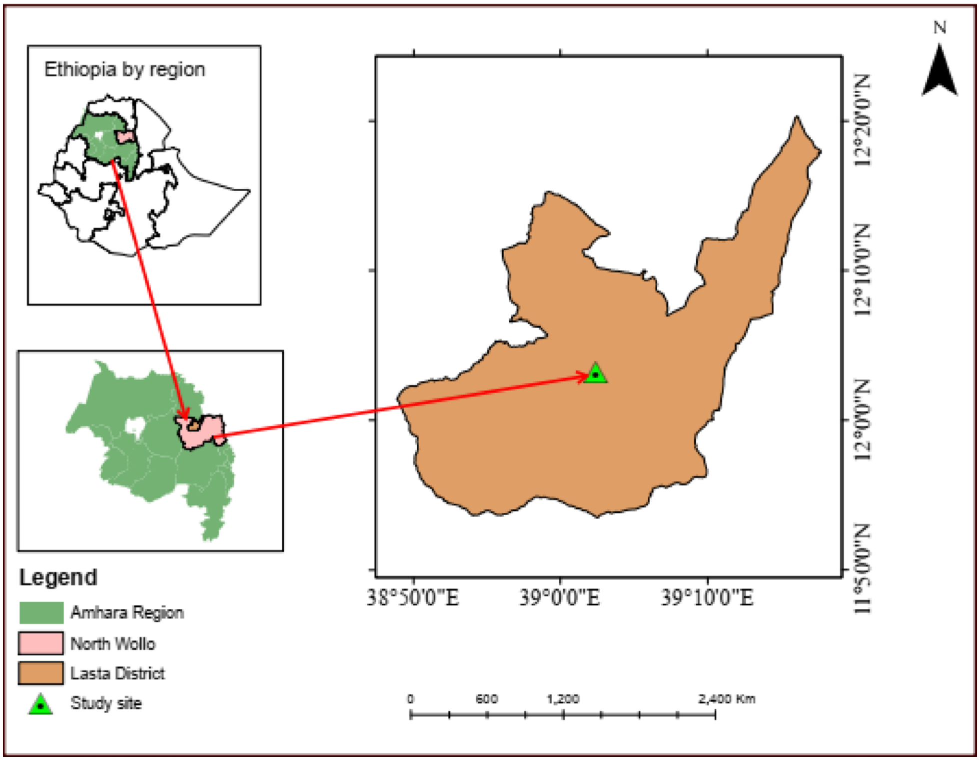

Fig. 1. Map of the study area. Source (Project = UTM, Zone = 37 N, datum = WGS 1984, ArcGIS 10.7.1 (Esri, 2019).

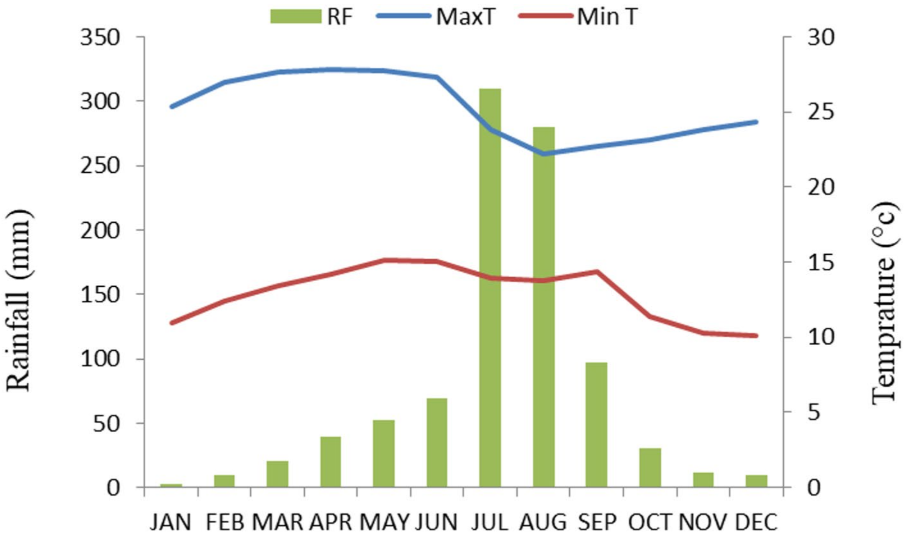

Fig. 2. Average thirty-one-year monthly rainfall and temperature data (Kombolcha Meteorological Station).

	Treatments			
No.	***N* rate (%RN)**	**VC in *N* equivalence**	***N* kg ha^{-1}**	**VC t ha^{-1}**
1	0	0	0	0
2	0	50%	0	3.52
3	0	100%	0	7.04
4	50%	0	34.5	0
5	50%	50%	34.5	3.52
6	50%	100%	34.5	7.04
7	75%	0	51.75	0
8	75%	50%	51.75	3.52
9	75%	100%	51.75	7.04
10	100%	0	69	0
11	100%	50%	69	3.52
12	100%	100%	69	7.04

Table 1. Treatments with a factorial arrangement.

Meteorological Station). The area is also characterized by uneven distribution and erratic rainfall[29] and is grouped as a moisture-stressed area. The maximum rainfall was recorded in July and August, followed by September and June (Fig. 2). The predominant soil types in the area are Vertisols, Cambisols, Rogosols and Lithosols[30]. The soil is shallow and has a low available soil nutrient status. The area is usually referred to by its undulating topography, very shallow soil depth, high soil erosion, and scattered forest coverage.

Experimental materials and procedures

The Sekota-1 bread wheat variety was used as the test crop and sown at a rate of 125 kg ha^{-1}. All treatments used 23 kg ha^{-1} P_2O_5, as recommended in the area. The recommended-Nitrogen (RN) of mineral fertilizer in the area is also 69 kg ha^{-1}[26]. The sources of N and P fertilizers were urea and TSP, respectively. The VC was provided by farmers. This VC was prepared from locally available materials such as cow dung, enbacho (locally available shrubs whose leaves do not crumble during the dry season) and potato residue, and processed with the help of vermiworms. The urea and TSP fertilizers and wheat seed were secured from the Sekota Dryland Agricultural Research Center (SDARC).

The experiment was conducted during the 2023 cropping season in a farmer's field on the vertisols soil type. The trial comprised four levels of RN (0, 50%, 75% and 100%) along with three levels of VC based on N equivalence (0, 50%, and 100%). These treatments were arranged in a factorial manner and implemented using a randomized complete block design. In total, there were twelve treatments, each of which was replicated three times (Table 1). Each plot had a gross area of 3 m × 3.2 m (9.6 m^2), with 0.2 m, 0.5 m, and 1 m spacing between rows, plots, and blocks, respectively, and 16 rows per plot. A full dose of P and half of the N were applied at planting, and the remaining half of the N was applied at vegetative stages (35 days after planting). Vermicompost was incorporated into the soil at a depth of 0–10 cm and then covered with soil one week prior to planting the test crop, following the procedure described by[31]. Throughout the growing period, the entire set of treatments included three rounds of weeding.

Sampling, preprocessing and analysis

Both disturbed (composite) and undisturbed soil samples were collected from the depth of 0–20 cm. Before planting, one composite soil sample was collected, and after crop harvest, 36 soil samples were collected via the zigzag method from each treatment plot to form one composite soil sample in three replications. The undisturbed core soil samples were used to determine the bulk density and porosity. The disturbed composite soil samples collected were air-dried, mixed well and passed through a 2 mm sieve for all parameters that were determined except for total nitrogen and organic carbon, which passed through a 0.5 mm sieve. The soil particle size distribution was analyzed via the hydrometer method[32]. The soil pH was measured at a 1:2.5 (soil-to-water) ratio using a glass calomel combination electrode[33]. Soil organic carbon was determined following the wet digestion method[34]. Total nitrogen was analyzed using the Kjeldahl method.

Available P was determined by Olsen's method[35]. The cation exchange capacity (CEC) was determined after the samples were extracted with 1 N ammonium acetate[36]. The determination of exchangeable K and Na was performed by a flame photometer. The exchangeable Ca and Mg concentrations were also determined following standard procedures. The nutrient analysis of VC was similarly adopted for the nutrient analysis of soil. The disturbed soil sample laboratory analyses were performed at the Bahir-Dar University Soil and Plant Laboratory, and the undisturbed soil sample laboratory analysis was performed at the SDARC soil laboratory.

Soil and vermicompost physicochemical properties before treatment application

Based on the laboratory results, the experimental soil textural class is classified as sandy clay loam[37]. The pH of the soil was 7.35, which is neutral and suitable for the cultivation of most crops[38]. The soil bulk density before treatment application is 1.32 g/cm^3, which is normal for the cultivation of crops[39]. The organic carbon content of the soil was 1.11%, which is classified as moderate[39]. The available phosphorus of the soil is rated as high[40]. The total nitrogen in the area was 0.11%, which was grouped into low categories[39]. The CEC of the soil was 27.8 cmol$_c$ /kg, which is considered high[40]. The exchangeable K of the experimental site before treatment application was 0.959 cmol$_c$/kg and was rated as high. The exchangeable Na content of the site was also recorded as 0.504 cmol$_c$/kg. Similarly, the exchangeable Ca and Mg of the soil before treatment application were 2.46 and 13.36 cmol$_c$/kg, respectively, which are considered high, and the application of nutrients such as nutrient-containing fertilizer is not effective[40]. The electrical conductivity of the experimental soil was 58.70 μ S/m, and the soil was rated as non-saline or salt free[40].

The VC that we used during the experiments had a pH of 7.45. It has 0.98% total nitrogen content with 268.7 ppm of available phosphorus. The VC contains 14.14% OC. It is also characterized by 7.81, 2.65, and 38.40 cmol$_c$ /kg exchangeable potassium, sodium, and CEC, respectively. The exchangeable magnesium and calcium contents of the VC were 8.41 and 17.36 cmol$_+$/kg, respectively (Table 2).

Data collection

The following agronomic data were collected: phenology (days of 50% heading, day of physiological maturity), shoot parameters (number of tillers per m2, plant height), yield components (spike length, kernel per spike, and thousand kernel weight), and yield parameters (biomass and grain yield). The number of days to 50% heading (days) was measured by counting and recording the number of days from planting until the date on which 50% of the plants in a plot started heading. Days of maturity were taken by counting the number of days from planting until the date on which 90% of the plants in a plot had physiologically matured. Plant height, spike

Parameters	Unit	Soil result	Vermicompost
Texture			
Sand	%	46	
Silt	%	22	
Clay	%	32	
Textural class	–	Sand clay loam	
BD	g/cm^3	1.32	
TN	%	0.11	0.98
Av.P	Ppm	20.48	268.7
OC	%	1.11	14.14
K	cmol$_c$/kg	0.959	7.81
Ca	cmol$_c$/kg	13.36	17.36
Mg	cmol$_c$/kg	2.48	8.41
Na	cmol$_c$/kg	0.504	2.65
CEC	cmol$_c$/kg	27.8	38.4
EC	μ s/m	58.70	-
pH	–	7.35	7.45

Table 2. Initial soil and vermicompost physicochemical properties.

length number of kernels per spike was measured from 10 randomly selected plants at physiological maturity. The number of tillers per square meter was determined by counting the spikes within a 0.8 m × 1.25 m area of the net plot. Thousand kernel weights (g) were determined by counting 1000 kernels using an electronic seed counter randomly selected from the net plot harvest and the adjusted yield of the harvest at 12.5% grain moisture content and weighing them with an electronic balance. The determination of aboveground biomass involved weighing the total air-dried biomass harvested from the net plot areas. The weight of the grains from plants within a net plot area at harvest maturity was measured and converted to kilograms per hectare (kg ha^{-1}) after adjusting the moisture content to 12.5%.

Data analysis

All the collected data were subjected to analysis of variance (ANOVA) at the 0.01 and 0.05 significance level using R software (version 4.3.2). When there were differences in treatments, means were separated by the Duncan multiple range test (DMRT).

Economic analysis

To complete the economic analysis, the actual biomass and grain yield were adjusted by 10% to equalize the experimental yields with those expected by farmers from the same treatment. For each treatment, the gross benefit (GB), total costs that vary (TCV), net benefit (NB), and marginal rate of return (MRR) were analyzed separately. The total costs that varied among all treatments were fertilizer purchase, VC preparation costs, transportation costs, and application costs (ETB ha^{-1}). All the costs were valued based on the current price of each item. The cost of nitrogen in the form of urea was 121 birr/kg. Following the work norm, 500 ETB was needed to prepare 1 t of VC, and 500 ETB was also needed to transport and incorporate VC into the field. The current prices of 1 kg of wheat grain and straw were 76 and 6 ETB, respectively. The subsequent two-year period may enhance yields as a result of residual effects from the addition of VC[41], and the cost of VC is divided by three. The net benefit (NB) was calculated as the difference between the gross benefit (GB) and total variable cost (TVC) of each treatment in the ETB ha^{-1}. The dominated treatments were removed from the MRR analysis. For each pair of ranked treatments, a marginal rate of return (MRR) was calculated as the difference in net benefit to the change in total variable cost CIMMYT[42].

Results and discussion

Response of soil physicochemical properties to nitrogen and vermicompost application

Based on the ANOVA results, the main effects of mineral N and VC on the bulk density, soil porosity, pH and total N of the soil were significant, but their interaction did not have a significant effect. Mineral N and VC had significant effects on the EC, %OC, CEC, and exchangeable Na of the soil. The main effect of VC was a significant effect on the available P, exchangeable Ca, exchangeable Mg and exchangeable K of the soil (Table 3).

Response of soil physical properties to mineral nitrogen and vermicompost

Increasing the vermicompost (VC) application rate from 0 to 100% nitrogen equivalence led to a decrease in soil bulk density from 1.37 ± 0.02 g cm^{-3} to 1.28 ± 0.02 g cm^{-3} and an increase in soil porosity from 48.53 ± 0.56% to 51.48 ± 0.65% (Table 4). This trend suggests that higher rates of VC application reduce soil compaction, thereby improving soil structure, enhancing porosity, and potentially creating more favorable conditions for root growth and nutrient uptake.

In contrast, increasing the mineral nitrogen (N) rate from 0 to 100% recommended nitrogen (RN) slightly increased the bulk density from 1.31 g cm^{-3} to 1.32 g cm^{-3} and slightly decreased soil porosity from 50.69 ± 1.55% to 49.96 ± 1.47%. However, these changes were not statistically significant at lower N application rates (0%, 50%,

SV	DF	Bulk density	Porosity	EC	%OC	pH	%*N*
N	3	0.0005*	0.8038*	14.50**	0.0313**	0.0395**	0.00029**
VC	2	0.0268**	30.55**	361.09**	0.7200**	0.0508**	0.00176**
Rep	2	0.0002^{ns}	0.234^{ns}	3.36^{ns}	0.0040*	0.0529**	0.00041*
N*VC	6	0.0003^{ns}	0.4587^{ns}	6.09*	0.0281**	0.0028^{ns}	0.00007^{ns}
Error	22	0.000143	4.64483	1.63	0.0008	0.0035	0.00004

SV	DF	Av.P	CEC	Ex.Na	Ex.K	Ex.Ca	Ex.Mg
N	3	0.89^{ns}	18.19**	0.0336**	0.0008^{ns}	0.15^{ns}	0.019^{ns}
VC	2	31.49**	270.56**	0.1374**	0.0525*	7.77*	3.821*
Rep	2	0.05^{ns}	0.20^{ns}	0.0003^{ns}	0.0002^{ns}	0.09^{ns}	0.083^{ns}
N*VC	6	1.41*	5.99*	0.0397**	0.0077^{ns}	1.23^{ns}	0.004^{ns}
Error	22	0.34	0.95	0.0012	0.0064	0.67	0.033

Table 3. Analysis of variance in soil physicochemical properties under mineral nitrogen and vermicompost fertilizer application. SV, sources of variation; DF, degrees of freedom; EC, electrical conductivity; %OC, organic carbon; %N, total nitrogen; Av. P, available phosphorus; CEC, cation exchange capacity; Ex. Na, exchangeable sodium; Ex. K, exchangeable potassium.

N (%RN)	Bulk density (g cm^{-3})	Porosity (%)	pH (1:2.5)	TN (%)	Ex.K ($cmol_c$/kg)	Ex.Ca ($cmol_c$/kg)	Ex.Mg ($cmol_c$/kg)
0	1.306 ± 0.045^{b}	50.69 ± 1.55^{a}	7.41 ± 0.09^{a}	0.113 ± 0.02^{b}	1.140 ± 0.14	14.21 ± 1.56	3.03 ± 0.53
50%	1.313 ± 0.041^{ab}	50.39 ± 1.39^{ab}	7.38 ± 0.12^{a}	0.117 ± 0.01^{b}	1.147 ± 0.10	14.34 ± 1.27	3.07 ± 0.50
75%	1.313 ± 0.043^{ab}	50.39 ± 1.46^{ab}	7.30 ± 0.08^{b}	0.120 ± 0.01^{ab}	1.125 ± 0.05	14.02 ± 0.73	3.09 ± 0.46
100%	1.324 ± 0.043^{a}	49.96 ± 1.47^{b}	7.27 ± 0.09^{b}	0.126 ± 0.02^{a}	1.142 ± 0.02	14.23 ± 0.34	3.14 ± 0.56
Sig ($p < 0.05$)	*	*	**	**	Ns	ns	ns
VC (N equi)							
0	1.37 ± 0.02^{a}	48.53 ± 0.56^{b}	7.27 ± 0.10^{b}	0.107 ± 0.01^{c}	1.073 ± 0.09^{b}	13.40 ± 0.91^{b}	2.44 ± 0.17^{c}
50%	1.29 ± 0.01^{b}	51.06 ± 0.44^{a}	7.38 ± 0.11^{a}	0.120 ± 0.01^{b}	1.138 ± 1.138^{ab}	14.18 ± 1.10^{ab}	3.30 ± 0.15^{b}
100%	1.282 ± 0.02^{b}	51.48 ± 0.65^{a}	7.39 ± 0.08^{a}	0.131 ± 0.01^{a}	1.207 ± 0.02^{a}	15.01 ± 0.34^{a}	3.51 ± 0.18^{a}
Sig ($p < 0.05$)	**	*	**	**	*	*	**
CV (%)	3.16	2.84	1.49	11.41	3.85	3.39	4.84

Table 4. Main effect of mineral nitrogen and vermicompost application on the physicochemical properties of the soil (mean ± SD). TN (%), total nitrogen; Ex.K, exchangeable potassium; Ex.Ca, exchangeable calcium; Ex. Mg, exchangeable magnesium, ns, no significant; *Significant difference at $p < 0.05$, ** highly significant difference at $p < 0.01$.

and 75% RN). A statistically significant difference was observed only between the 100% RN treatment and the control (Table 4).

This suggests that mineral fertilizer had a minimal impact on the bulk density and soil porosity, with higher doses potentially even increasing the soil bulk density and decreasing the soil porosity. The decrease in bulk density resulting from the use of organic fertilizer may be attributed to increased porosity associated with increased organic matter. Several researchers have confirmed that the addition of VC and nitrogen fertilizer can influence the bulk density of soil. Gopinath et al.[43] demonstrated that the application of organic fertilizer reduced the BD of the soil compared to that of mineral fertilizer and unmanaged soil. Additionally, Tharmaraj et al.[44] observed that improvements in total porosity led to lower bulk density with the use of VC. Furthermore, Ejigu et al.[45] verified that applying higher rates of compost along with mineral fertilizers reduced the bulk density compared to that under sole application or no fertilizer treatments. Moreover, Emamu and Wakgari[24], reported that the highest bulk density was recorded in the control treatment group, whereas the lowest bulk density was observed in the VC treatment group. In line with this finding, Lim et al.[46] concluded that the maximum VC application resulted in the maximum soil porosity. Similarly, the maximum soil pore space was recorded from the treatment that received maximum VC compared to the control[47]. Similarly, Tana and Woldesenbet[48] confirmed that applying higher rates of organic fertilizer with 25% and 50% mineral fertilizer resulted in lower BD and improved soil porosity than did the control.

Response of soil chemical properties to mineral nitrogen and vermicompost

Soil pH ranged from 7.27 ± 0.09 to 7.41 ± 0.09 in the 100% RN and control treatment groups, respectively, and from 7.27 ± 0.09 to 7.39 ± 0.08 in the control and 100% VC treatment groups. However, no statistically significant differences were observed among the VC application rates (Table 4). These results suggest that the application of inorganic fertilizer significantly reduced soil pH, while the addition of organic fertilizer (vermicompost) tended to increase it. The pH values observed for all treatment combinations were within the ranges of neutral soil reactions[38]. This result is consistent with the finding of Tana and Woldesenbet[48] that the application of the recommended mineral fertilizer reduced the pH of the soil compared with other treatment combinations. Additionally, compared with mineral fertilizer application, the application of compost and VC increased the pH of the soil[49]. The addition of VC significantly affects the soil pH[50].

The highest total nitrogen levels (0.126 ± 0.02% and 0.131 ± 0.01%) were recorded with the application of 100% RN and 100% VC as nitrogen equivalents, respectively. In contrast, the lowest total nitrogen contents (0.113 ± 0.02% and 0.107 ± 0.01%) were observed in the control treatments for inorganic and organic fertilizers. Compared to the control, the application of 100% RN and 100% VC increased total nitrogen by 11.50% and 22.43%, respectively (Table 4). The increase in total nitrogen observed after the application of RN and VC indicates the effectiveness of both types of fertilizers in enriching the soil nitrogen content. The increase in total nitrogen can be attributed to the increase in nitrogen contents in VC and mineral N. When VC is added to the soil, nitrogen becomes available for plant uptake, contributing to an increase in the total nitrogen content. Mineral N fertilizers directly supply nitrogen in inorganic forms that are readily available for plant uptake and can quickly increase soil nitrogen levels. This suggests that additional nitrogen inputs or management strategies may be necessary to meet the nitrogen requirements of crops and increase the soil nitrogen content. This finding aligns with, Gautam et al.[51,47] they reported that supplementing with additional organic fertilizers, particularly the full recommended dose of VC, increases the total nitrogen content in soil, which is consistent with previous research indicating that both organic and inorganic fertilizers increase total nitrogen levels[27].

The highest EC value (66.30 µS/cm) was recorded when 100% RN was applied with 100% VC as the N equivalence, while the lowest EC (51.10 µS/cm) was observed in the control treatment. It was evident that increasing the rates of both organic and inorganic fertilizers resulted in higher EC levels in the soil (Table 5). The increase in electrical conductivity due to the application of both mineral N and VC fertilizers might release

Treatments		**EC (μ S/cm)**	**Av.*P* (ppm)**	**OC (%)**	**CEC (Cmol$_c$ /kg)**	**Ex.Na (Cmol$_c$ /kg)**
N	**VC**					
0	0	51.10 ± 1^{d}	19.17 ± 0.21^{e}	1.05 ± 0.01^{g}	23.37 ± 1.26^{d}	0.53 ± 0.01^{c}
0	50%	62.10 ± 1^{b}	20.50 ± 0.56^{cde}	1.44 ± 0.02^{cd}	32.80 ± 1.00^{bc}	0.55 ± 0.001^{c}
0	100%	62.20 ± 1^{b}	22.97 ± 0.41^{a}	1.50 ± 0.05^{bc}	34.4 ± 1.00^{ab}	0.53 ± 0.04^{c}
50%RN	0%	54.00 ± 1^{cd}	19.88 ± 0.47^{de}	1.08 ± 0.01^{g}	24.5 ± 1.15^{d}	0.55 ± 0.01^{c}
50%RN	50%	60.90 ± 1^{b}	20.81 ± 0.41^{cde}	1.33 ± 0.02^{ef}	33.00 ± 1.00^{b}	0.53 ± 0.01^{c}
50%RN	100%	63.27 ± 2.92^{ab}	22.08 ± 0.53^{abc}	1.41 ± 0.01^{de}	34.00 ± 1.00^{ab}	0.58 ± 0.04^{c}
75%RN	0%	55.87 ± 0.57^{c}	19.51 ± 0.06^{de}	1.09 ± 0.01^{g}	25.60 ± 1.00^{d}	0.53 ± 0.01^{c}
75%RN	50%	61.53 ± 1.41^{b}	21.14 ± 0.52^{bcd}	1.36 ± 0.05^{de}	33.03 ± 0.45^{b}	0.53 ± 0.01^{c}
75%RN	100%	63.90 ± 1^{ab}	22.90 ± 0.55^{a}	1.56 ± 0.02^{b}	34.33 ± 0.65^{ab}	0.79 ± 0.01^{b}
100%RN	0%	53.70 ± 1^{cd}	19.23 ± 0.22^{e}	1.09 ± 0.01^{g}	30.00 ± 1.00^{c}	0.53 ± 0.01^{c}
100%RN	50%	64.18 ± 1.54^{ab}	22.71 ± 1.20^{ab}	1.37 ± 0.07^{de}	33.20 ± 0.40^{b}	0.54 ± 0.01^{c}
100%RN	100%	66.30 ± 1^{a}	22.77 ± 0.72^{ab}	1.79 ± 0.01^{a}	36.80 ± 1.00^{a}	0.96 ± 0.1^{a}
Sig ($p < 0.05$)		**	**	**	**	**
CV (%)		8.20	7.23	16.76	3.04	3.19

Table 5. Response of the integrated application of N and VC to selected chemical properties of the soil (mean ± SD). EC, electrical conductivity; %OC, organic carbon; Av.P, available phosphorus; CEC, cation exchange capacity; Ex.Na, exchangeable sodium.

ions such as nitrate, magnesium, calcium, sodium and potassium into the soil solution. However, these released ions could enhance nutrient availability for wheat plants, leading to improved growth and yield. Similarly, in this study, the application of VC and inorganic fertilizer increased the EC of the soil[52]. Additionally, the application of mineral fertilizer increased the EC of the soil[53]. Moreover, the application of VC increases the EC of the soil[54]. In contrast, the application of a relatively high proportion of mineral N and VC reduced the EC of the soil[55].

The highest OC (1.79 ± 0.01%) was recorded with the combined application of 100% RN and 100% VC as the N equivalent, while the lowest value (1.05 ± 0.01%) was observed in the control. The application of 50% and 100% VC as N equivalents increased OC by 37.14% and 42.86%, respectively. Likewise, the integration of 100% RN with 100% VC resulted in OC increases of 70.47% and 64.22% compared to the control and sole 100% RN application, respectively (Table 5). These results suggest that combining VC with mineral N fertilizer can have a synergistic effect on soil organic carbon levels. The organic matter in VC serves as a valuable carbon source for the soil, while mineral N fertilizer promotes plant growth and biomass production, leading to increased organic carbon content. This integrated use of VC and N fertilizer presents a promising strategy for enhancing soil health and fertility in agricultural systems. The findings are consistent across multiple studies, indicating that applying a maximum amount of VC, either alone or integrated with inorganic fertilizers, results in higher organic matter content[27,56,57].

The maximum available phosphorus (22.97 ± 0.55 ppm) was observed with the application of 100% VC as the N equivalence, but was statistically paralleled with the application of 100% RN with 50% and 100% VC as the N equivalence and 50% and 75% RN with 100% VC as the N equivalence. The lowest available phosphorus (19.17 ± 0.21 ppm) was recorded in the control. The application of 50% and 100% tons of VC increased the available phosphorus by 6.9 and 19.8%, respectively, compared with the control treatments (Table 5). The increase in available phosphorus might be because VC is rich in organic matter, which improves the soil structure and increases its ability to hold nutrients, including phosphorus, and can release phosphorus to the soil during mineralization. This result was consistent with the findings of Mengistu et al.[58], who reported that increasing the VC rate also increased the maximum available phosphorus. Additionally, VC has shown superiority in providing available phosphate in the soil[59]. Furthermore, a combination of enriched VC with reduced inorganic phosphorus fertilizer has been found to enhance phosphorus release and availability in naturally phosphorus-deficient soils[60].

Response of CEC and exchangeable bases to mineral nitrogen and vermicompost

The highest cation exchange capacity (CEC) value (36.80 ± 1.00 cmol$_c$ /kg) was recorded from the combined application of 100% RN and 100% VC as nitrogen equivalents. This value was statistically similar to those observed with 75% RN + 100% VC, 50% RN + 100% VC, and 100% VC alone. In contrast, the lowest CEC (23.37 ± 1.26 cmol$_c$ /kg) was recorded in the control treatments. The integrated application of mineral nitrogen fertilizer and vermicompost increased the soil CEC by 57.46% compared to the control and by 22.67% compared to the 100% RN treatment alone (Table 5). The integrated application of these fertilizers might increase the soil CEC due to the high CEC of the organic matter. OM possesses a high CEC because of its negative charge, which actively attracts and retains positively charged ions. Additionally, the organic matter in VC fertilizer can help to increase the soil's ability to retain nutrients. This increase in CEC can lead to better nutrient availability for plants and improved soil fertility overall. This result was similar to that of Mengistu et al.[58], who confirmed that the sole application of VC and mineral N fertilizer resulted in the maximum CEC of the soil. Similarly, the application of organic and mineral fertilizers increased the CEC of the soil[48]. Furthermore, applying a relatively high VC application rate significantly improved the CEC of the soil[54]. Additionally, the integrated application of mineral fertilizer with compost increased the residual effect of CEC in the soil[61].

The highest exchangeable K value (1.207 ± 0.02 cmol_c /kg) was obtained from the application of 100% vermicompost (VC), although it was statistically similar to the value recorded with 50% VC at the nitrogen equivalence. The lowest exchangeable K (1.073 ± 0.09 cmol_c /kg) was observed in the control treatment. Overall, the application of VC increased the soil's exchangeable K by 12.48% (Table 4).This is attributed to the fact that VC contains valuable exchangeable K, which is released into the soil upon application, thereby increasing the exchangeable K content in the soil. This result was consistent with the finding of Kumar et al.[47] that the application of VC increased the exchangeable K of the soil. Similarly, studies have indicated that VC releases and converts nutrients into soluble forms, providing available K for plants[62]. Additionally, VC has been found to enhance K availability[63]. Moreover, compared with the sole recommended mineral fertilizer, the application of VC increased the available K[64].

The highest exchangeable Ca (15.01 ± 0.34 cmol_c/kg) and Mg (3.51 ± 0.18 cmol_c/kg) were recorded with the application of 100% vermicompost (VC) at the nitrogen equivalence rate, while the lowest values for Ca (13.40 ± 0.91 cmol_c/kg) and Mg (2.44 ± 0.17 cmol_c/kg) were observed in the control treatment (Table 4). The increase in exchangeable Ca and Mg with VC application may be attributed to its ability to supply exchangeable bases and reduce their leaching from the soil. The application of a greater percentage of compost resulted in higher exchangeable Ca contents compared with the lowest rates[56]. Similarly, the application of higher rates of VC increased the Ca and Mg content compared to the control and lower rates[58]. Furthermore, as the dose of VC increased, the exchangeable Ca and Mg content increased[54].

The maximum exchangeable Na (0.96 ± 0.1) was recorded from 100% RN with 100% VC as the N equivalence. The lowest exchangeable Na concentration was recorded in the control (0.53 ± 0.01) (Table 5). The result showed that adding higher rates of mineral N and higher rates of VC increased the exchangeable Na of the soil. Some scholars have confirmed that the application of higher rates of compost and mineral fertilizer results in increased exchangeable Na in the soil[61]. If the ESP% remains below 15%, the increase in exchangeable Na resulting from VC addition may not be harmful to crops. This is because the addition of VC has the potential to increase exchangeable bases relative to exchangeable sodium. Studies have indicated that VC application can lead to a decrease in the exchangeable sodium percentage (ESP)[54].

Levels not connected by the same letter are significantly different.

Effects of mineral nitrogen and vermicompost on wheat yield

Based on the ANOVA results, the main effects of mineral nitrogen and vermicompost application and their interaction had no significant ($p > 0.05$) effect on days to heading and maturity. Mineral N had a highly significant ($p < 0.01$) effect on spike length, number of kernels per spike, and thousand-kernel weight, while VC had a significant ($p < 0.05$) effect on those parameters, but their interaction did not. The main and interactions of these fertilizers had highly significant ($p < 0.01$) effects on the tiller number, plant height, biomass yield, and grain yield of wheat (Table 6).

Effects of mineral nitrogen and vermicompost on wheat phenology

The maximum number of days required for 50% heading was observed with the application of 100% RN and 100% VC with N equivalence, with values of 57.67 ± 1.01 and 57.42 ± 0.90 days, respectively. Conversely, the control plots (without fertilization) exhibited the minimum number of days for 50% heading, with recorded values of 56.56 ± 0.73 and 56.83 ± 1.03 days for N and VC, respectively. Similarly, maximum maturity dates of 97.67 ± 1.58 and 97.58 ± 1.38 days were recorded with the application of 100% RN and 100% VC, respectively, at N equivalence. In contrast, the control treatments had minimum days to maturity of 96.56 ± 0.88 and 96.67 ± 0.78 days, respectively (Table 7). This delay in heading and maturity could be attributed to the essential role of nitrogen in plant growth. Excess N might lead to delayed heading and maturity, as plants prioritize vegetative growth over reproductive development. This result is in line with previous studies by Biri et al.[65] and Harfe[66], who reported that increasing nitrogen application rates prolonged the heading and maturity dates of wheat plants. Additionally, Ding et al.[67] reported that, compared with the control, the application of VC delayed the heading and maturity of wheat plants. Similarly, ÇIRKA et al.[13] reported that the lowest heading and maturity dates were recorded in the control group, which also had the lowest VC rate. Furthermore, Fazily et al.[68] demonstrated that the application of additional mineral and organic fertilizers increased wheat maturity compared to that of untreated controls. However, contrasting results were reported by[69,70], who reported that,

SV	DF	DH	DM	T/m^2	PH (cm)	SL (cm)	BM	KPS	GY	TKW
N	3	2.77^{ns}	2.15^{ns}	12247.84^{**}	293.11^{**}	0.81^{**}	20.75^{**}	139.64^{**}	$3,716,795^{**}$	22.61^{**}
VC	2	1.09^{ns}	2.53^{ns}	1466.58^{**}	41.77^{*}	0.34^{*}	2.19^{**}	69.53^{*}	510877.5^{**}	10.84^{*}
Rep	2	0.25^{ns}	0.20^{ns}	102.69^{**}	12.64^{*}	0.14^{*}	0.03^{ns}	81.21^{*}	27076.5^{**}	1.03^{ns}
N*VC	6	0.38^{ns}	1.23^{ns}	89.38^{**}	60.91^{**}	0.05^{ns}	0.16^{**}	10.85^{ns}	$20,575^{**}$	0.28^{ns}
Error	22	0.79	0.92	19.34	23.68	0.03	0.013	6.57	1381	0.39

Table 6. Mean square value of ANOVA for most agronomic parameters based on N and VC fertilizers. DH, days to heading (days); DM, days to maturity (days); T/m^2, tiller per meter square; PH (cm) plant height, SL, spike length in centimeters; BM, above ground biomass; KPS, kernel per spike; GY, grain yield; TKW, thousand kernel weight; ns, no significant at $p > 0.05$; * significant at $P < 0.05$, **significant at $P < 0.01$.

N rate (%RN)	DH	DM	SL (cm)	KPS (count)	TKW (g)
0	56.56 ± 0.73	96.56 ± 0.88	8.10 ± 0.24^{b}	41.90 ± 4.14^{b}	34.25 ± 1.21^{d}
50%RN	56.67 ± 0.87	96.89 ± 0.78	8.62 ± 0.23^{a}	47.52 ± 4.36^{b}	35.74 ± 0.77^{c}
75%RN	57.44 ± 0.71	97.33 ± 0.50	8.59 ± 0.12^{a}	$47.89 \pm 3.27\ ^{b}$	36.98 ± 0.84^{b}
100%RN	57.67 ± 1.01	97.67 ± 1.58	8.80 ± 0.37^{a}	51.42 ± 4.13^{a}	37.91 ± 1.22^{a}
Sig ($p < 0.05$)	Ns	Ns	*	**	**
VC (N equi)					
0	56.83 ± 1.03	96.67 ± 0.78	8.35 ± 0.32^{b}	44.40 ± 4.60^{b}	35.23 ± 1.56^{c}
50%	57.00 ± 0.85	97.08 ± 0.79	8.54 ± 0.26^{a}	48.58 ± 5.57^{a}	36.33 ± 1.41^{b}
100%	57.42 ± 0.90	97.58 ± 1.38	8.69 ± 0.41^{a}	48.58 ± 4.42^{a}	37.12 ± 1.69^{a}
Sig ($p < 0.05$)	Ns	Ns	*	**	**
CV (%)	1.56	1.00	2.16	5.43	4.71

Table 7. Effect of mineral nitrogen and vermicompost fertilizers on selected yield traits of wheat.

Treatments					
N(RN)	VC (*N* equi.)	T/m^2	PH (cm)	BM (t ha^{-1})	GY (kg ha^{-1})
0	0	263.83 ± 4.06^{h}	78.87 ± 1.94^{f}	5.17 ± 0.23^{i}	1964.87 ± 66.47^{i}
0	50%	277.40 ± 1.42^{g}	83.93 ± 0.50^{e}	6.03 ± 0.12^{h}	2390.93 ± 57.14^{h}
0	100%	297.03 ± 2.25^{f}	85.93 ± 1.68^{cde}	6.47 ± 0.06^{g}	2469.43 ± 88.34^{h}
50%	0	317.57 ± 3.67^{e}	85.37 ± 1.70^{de}	6.93 ± 0.06^{f}	2841.20 ± 47.17^{g}
50%	50%	330.53 ± 2.08^{de}	$86.87 \pm 1.21^{b-e}$	7.87 ± 0.06^{e}	3207.70 ± 68.26^{f}
50%	100%	337.34 ± 7.26^{cd}	87.67 ± 2.03^{bcd}	7.93 ± 0.06^{e}	3257.37 ± 52.76^{ef}
75%	0	336.27 ± 2.70^{cd}	88.97 ± 1.21^{ab}	8.60 ± 0.17^{d}	3357.53 ± 31.30^{e}
75%	50%	342.90 ± 6.10^{bc}	$86.80 \pm 0.55^{b-e}$	8.80 ± 0.10^{cd}	3499.57 ± 69.69^{d}
75%	100%	345.00 ± 6.58^{bc}	87.97 ± 0.19^{bcd}	9.10 ± 0.10^{bc}	3676.10 ± 66.75^{bc}
100%	0	353.73 ± 9.08^{b}	89.67 ± 0.50^{ab}	9.00 ± 0.17^{bc}	3566.27 ± 8.13^{cd}
100%	50%	367.93 ± 2.08^{ab}	91.07 ± 0.74^{a}	9.30 ± 0.10^{ab}	3680.00 ± 65.77^{b}
100%	100%	380.37 ± 6.84^{a}	91.83 ± 0.48^{a}	9.53 ± 0.06^{a}	3955.33 ± 49.22^{a}
Sig ($p < 0.05$)		**	**	**	**
CV (%)		1.56	1.41	1.53	2.26

Table 8. Contribution of integrated fertilizer application to yield and yield-related traits of wheat. Levels not connected by the same letter are significantly different. T/m^2, number of tillers per square meter; PH, plant height in centimeters; KPS, number of kernels per spike; the number separated by ± standard deviation, BM, aboveground biomass in tons per hectare; GY, grain yield in kg per hectare.

compared with unfertilized treatments, the application of additional N reduced the heading and maturity dates of wheat plants.

DH, days to heading (days); DM, days to maturity (days); ns, nonsignificant at $p > 0.05$; SL, spike length in centimeters; KPS, number of kernels per spike; *significant at $P < 0.05$, **significant at $P < 0.01$, CV (%), coefficient of variation in percent.

Response of mineral nitrogen and vermicompost to the growth of wheat

The highest tiller count (380.37 ± 6.84) and plant height (91.83 ± 0.48 cm) occurred when 100% RN was combined with 100% VC with N equivalence ha^{-1}, respectively. The control group (unfertilized treatment) exhibited the lowest tiller count (263.83 ± 4.06) and plant height (78.87 ± 1.94 cm). These findings underscore the crucial role of both nitrogen-containing fertilizer and VC in enhancing tiller numbers and plant height. The combined application of 100% VC with 100% RN increased the tiller number by 44.17% and 7.53%, and the plant height by 14.43 and 2.41 cm compared with that of the control and 100% RN alone, respectively. The single application of 100% RN had a similar effect on PH to the combined application of 50% RN and 50% VC, 50% RN and 100% VC, 75% RN and 50%, and 75% RN and 100% VC (Table 8).

The application of VC and mineral N fertilizer increases the tiller number and PH of wheat crops due to their potential to increase nutrient availability, improve soil health, and increase stress tolerance and the deficiency of inherent nitrogen in the soil and the ability of fertilizers to supply nutrients. Studies by Fazily et al.[71] and Madani et al.[72] show that using 100% RN and 25% VC maximizes tiller count per square meter. Other studies[73], found that combining 75% RN with 25% manure or 50% RN with 50% manure yields the most tillers. Hadis et al.[74] and Kabato et al.[75] support this, reporting increased wheat height with combined VC and mineral fertilizer use. Additionally, Aslam et al.[76] noted tallest plant height with 50% VC and mineral fertilizers combined.

Effects of mineral nitrogen and vermicompost on the yield components of wheat

The maximum values of SL, KPS, and TKW were 8.80 ± 0.37 cm, 51.42 ± 4.13 and 37.7 ± 1.22 g, respectively, with the application of 100% RN, while the lowest values of SL, KPS and TKW were 8.10 ± 0.24 cm, 41.90 ± 4.14 and 34.25 ± 1.21 g, respectively, in the control. Similar to those of the mineral N fertilizers, the maximum SL, KPS and TKW values of 8.69 ± 0.41 cm, 48.58 ± 4.42 and 37.12 ± 1.69 g, respectively, were recorded from the 100% VC, while the minimum SL, KPS and TKW values of 8.35 ± 0.32 cm, 44.40 ± 4.60 and 35.23 ± 1.56 g, respectively, were recorded from the control. Specifically, the application of 100% RN increased the spike length by 8.6% compared with the control, and both N-containing mineral fertilizer and VC fertilizer increased the amount of KPS by 22.72% and 9.41%, respectively, compared to the control (Table 7). This suggests that mineral N and VC fertilizer supplementation have a positive impact on the SL, KPS and TKW of wheat crops. The improvements in SL, KPS and TKW associated with increases in fertilizer rates may be due to the contribution of N and VC fertilizers to a balanced nutrient supply, which supports various stages of plant growth, including flowering kernel formation, and are crucial for protein structure, thus enhancing grain weight.

This research aligned with the findings of Joshi et al.[77], who reported that the maximum SL was recorded from the recommended mineral fertilizer, while the minimum SL was recorded from the control. In line with these results, Hussain et al.[78] observed a maximum spike length with the application of VC alongside a basal dose of mineral fertilizer. Additionally, Noureldin and Saudy[79] reported that the application of mineral N fertilizer significantly increased spike length compared with that of the control. According to Ahmad and Tripathi[80], , the application of organic fertilizer alone or in combination with different rates of mineral fertilizer resulted in greater KPS than did the control. Similarly, Kushwaha and Tripathi[81] reported that, mineral fertilizer application resulted in the highest KPS and TKW. Additionally, ÇİRKA et al.[13] reported that the maximum application of compost resulted in the maximum number of kernels per spike. Moreover, the application of more compost was found to enhance TKW in wheat crops[75]. Additionally, the main effect of higher VC and mineral fertilizer rates is an increase in grain weight in wheat[82]. Furthermore, other authors also confirmed that the application of nitrogen fertilizer increased the TKW of wheat[83].

Effects of mineral nitrogen and vermicompost on the yield parameters of wheat

The study showed that applying 100% RN together with 100% VC produced the highest biomass yield, reaching 9.53 ± 0.06 t ha^{-1}. This yield was statistically similar to the yield obtained from applying 100% RN with 50% VC as N equivalence. Additionally, using 100% RN alone resulted in a biomass yield comparable to that from combining 75% RN with either 50% or 100% VC. On the other hand, the lowest BM yield of 5.17 ± 0.23 t ha^{-1} was observed in the control. Remarkably, the combined application of 100% RN with 100% VC as N equivalence resulted in a substantial increase in BM yield by 4.26 t and 0.43 t ha^{-1} compared with the control and 100% RN application alone, respectively. This result emphasizes the significant biomass yield advantages achieved through the integrated application of N and VC, with an 84.3% increase compared to the control and a 5.9% increase compared to the application of 100% RN alone.

The highest grain yield (3955.33 ± 49.22 kg ha^{-1}) was achieved with the application of 100% RN in combination with 100% VC as the N equivalence. Following the 100% RN with 100% VC ha^{-1} treatment, the other treatments that also resulted in high grain yields, in descending order, were 100% RN with 50% VC, 75% RN with 100% VC, 100% RN (without VC), and 75% RN with 50% VC, with grain yields of 3680.00 ± 65.77, 3676.10 ± 66.75, 3566.27 ± 8.13, and 3499.57 ± 69.69 kg ha^{-1}, respectively. The lowest grain yield (1964.87 ± 66.47 kg ha^{-1}) was recorded in the control treatment (no fertilizer application). The application of 50% VC and 100% VC as N equivalents increased the grain yield by 426.06 and 504.56 kg ha^{-1}, respectively, compared with that of the control. This showed that the application of VC increased the grain yield by 21.68% and 25.68%, respectively, compared with that of the control. Compared with the control and 100% RN alone, the integrated application of 100% RN with 100% VC increased the grain yield by 101.3% and 10.91%, respectively. The grain yield achieved with 100% RN application was comparable to that obtained with 75% RN combined with either 50% VC or 100% VC as N equivalence. Similarly, the application of 75% RN was comparable to that of 50% RN with either 50% VC or 100% VC (Table 8). The increase in the BM and GY of wheat due to the combined application of fertilizer may be attributed to VC, which is rich in essential nutrients. When integrated with mineral N fertilizer, it provides a balanced and readily available nutrient source to wheat plants, promoting optimal growth development and grain formation.

These findings align closely with those of previous research conducted by Aslam et al.[64], which confirmed that the highest biological yield was achieved through the application of a full dose of both inorganic and organic fertilizers. Similarly, the maximum biomass was recorded from the application of the maximum rate of nitrogen fertilizer[65]. Furthermore, Ejigu et al.[61] reported that applying maximum rates of both mineral and organic fertilizers led to a significant increase in the biomass yield of tef. According to Bezabeh et al.[84] combining VC with mineral fertilizer led to greater grain yields than using mineral fertilizer alone. Similarly, integrating mineral fertilizer with compost significantly boosted wheat grain yield[75]. Additionally, applying compost, either alone or with mineral N, substantially increased grain yield across wheat cultivars[85].

Economic analysis

According to the partial budget analysis, the application of 100% RN with 100% VC at the N equivalence resulted in the greatest net benefit (290088.91 ETB) ha^{-1}, while the control treatment yielded the lowest net benefit (151677.11 ETB) ha^{-1}. Both integrated and sole applications of N and VC contributed to an increase in the net benefit of wheat. None of the integrated and sole applications of VC and N fertilizer were dominant, except for the 50% RN with 100% VC as the N equivalence, which was dominated by the treatment with the lowest cost investment of 50% RN. Based on the analysis, the highest MRR was recorded at 2650.16% from the application of 75% RN with 100% VC as N equivalence, whereas the lowest was 65.09% from the application of 100% RN

Treatments		Gross yield		Adjusted yield						
N(kg/ha)	VC(t/ha)	GY	SY	GY	SY	TVC (ETB ha^{-1})	GB (ETB ha^{-1})	NB (ETB ha^{-1})	DA	MRR (%)
0	0	1964.87	3.20	1768.38	2.88	0.00	151677.11	151677.11		–
0	3.52	2390.93	3.63	2151.84	3.27	1173.33	183141.61	181968.28		2581.63
0	7.04	2469.43	3.97	2222.49	3.57	2346.67	190347.01	188000.35		514.10
34.5	0	2841.20	4.07	2557.08	3.66	4174.50	216316.08	212141.58		1320.76
34.5	3.52	3207.70	4.67	2886.93	4.20	5347.83	244624.68	239276.85		2312.66
51.75	0	3357.53	5.23	3021.78	4.71	6261.75	257897.05	251635.30		1352.25
34.5	7.04	3257.37	4.70	2931.63	4.23	6521.17	248184.11	241662.94	D	–
51.75	3.52	3499.57	5.30	3149.61	4.77	7435.08	267990.59	260555.50		760.24
69	0	3566.27	5.47	3209.64	4.92	8349.00	273470.87	265121.87		499.65
51.75	7.04	3676.10	5.40	3308.49	4.86	8608.42	280605.24	271996.82		2650.16
69	3.52	3680.00	5.63	3312.00	5.07	9522.33	282114.00	272591.67		65.09
69	7.04	3955.33	5.60	3559.80	5.04	10695.67	300784.57	290088.91		1491.24

Table 9. Partial budget analysis of N and VC on the yield of wheat. TVC (ETB ha^{-1}), total variable cost in Ethiopian birr per hectare; GB (ETB ha^{-1}), gross benefit in Ethiopian birr per hectare; NB (ETB ha^{-1}), net benefit in Ethiopian birr per hectare, DA, dominance; MRR%, marginal rate of return in percent.

with 50% VC. Based on this analysis, 100% of RNs with 50% VC in the N equivalence treatment were excluded from the recommendation for farmer practices because the minimum acceptable marginal rate of return we stand for is 100% (Table 9).

Conclusion and recommendations

The integrated application of mineral nitrogen (N) with vermicompost (VC) significantly improves soil physicochemical properties and yield components of wheat. This integrated fertilizer management decreases soil bulk density, enhances porosity, and boosts soil nutrient levels, cation exchange capacity (CEC), and exchangeable bases. Applying 100% VC results in the lowest bulk density. Combining 100% VC with recommended nitrogen (RN) yields the highest total nitrogen (0.14 ± 0.01%). Applying 100% RN with 100% VC achieves the highest organic carbon (1.79 ± 0.01%) and cation exchange capacity (36.80 ± 1.00), while control plots record the lowest values. These improvements in soil physicochemical properties demonstrate the potential of this integrated approach to enhance soil fertility and productivity. Moreover, integrating mineral fertilizer with VC improves the yield and yield-related traits of wheat. The combination of 100% RN with 100% VC results in the maximum grain yield (3955.33 ± 49.22 kg ha^{-1}) and biomass yield (9.53 ± 0.06 t ha^{-1}). In contrast, unfertilized plots yield the minimum grain (1964.87 ± 66.47 kg ha^{-1}) and biomass (5.17 ± 0.23 t ha^{-1}). The significant increase in wheat yield, along with improvements in yield components, underscores the practical benefits of adopting integrated fertilizer management practices. Economically, the highest net benefit (290088.91 ETB ha^{-1}) comes from applying 100% RN combined with 100% VC. This integrated fertilizer application is feasible for farmers and reduces the cost of mineral fertilizer by improving soil nutrient levels. Based on the maximum wheat yield, better soil property improvement and maximum economic return, farmers should apply an integrated 100% RN with 100% VC as the N equivalent. Further research should be conducted across multiple locations and years to validate the efficacy of this integrated approach. Furthermore, long-term studies on permanent plots should be implemented to understand the residual effect, sustainability and potential long-lasting effects on soil health and crop productivity.

Data availability

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

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Author contributions

Ewunetie Melak: conceptualization, experiment implementation, monitoring, data collection, first draft manuscript writing, and final draft writing. Eyayu Molla: Supervising the work, methodology, and editing of the manuscript. Tesfaye Feyisa: Supervising the work, methodology, and editing the manuscript. Workat Sebnie: experiment implementation, monitoring, data collection, methodology, and editing the manuscript. Mamaru Shitaw: laboratory work, supervising the work, methodology, and manuscript editing.Tesfaye Shiferaw: Supervising the work, methodology, and editing the manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Informed consent

The field experiment was conducted on a farmer's field with prior informed consent and agreement from the landholding farmer. No additional institutional or governmental permission was required, as the study was carried out on private land through direct negotiation with the participating farmer.

Additional information

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