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The Ameliorative Effects of Lime and Vermicompost on Yield and Yield Components of Barley (*Hordeum vulgar* L.) and Soil Properties in Acidic Soil of Northwestern Ethiopia

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Soil acidity and fertility depletion are the major challenges to crop production in the northwestern highlands of Ethiopia. In response to this problem, this study was conducted on acidic soils of Banja district of northwestern Ethiopia to evaluate the main and interaction effects of different rates of lime and vermicompost application on soil properties, and yield and yield components of barley during 2020 main cropping season. The factorial combinations of four rates of lime (0, 50, 100, and 150%) or (0, 0.93, 1.86, and 2.79 t/ha^{-1}) with three rates of vermicompost (0, 2.5 and 5 t ha^{-1}) were laid out in randomized complete block design with three replications. Soil samples were taken at a depth of 0-15 cm before the application of treatments and after harvesting. The results revealed that the interaction effects of lime (2.79 t ha^{-1}) with VC (5 t ha^{-1}) significantly increased soil pH (5.55), exchangeable calcium (14.36%), and exchangeable sodium (0.58%). Similarly organic carbon (3.17%), and exchangeable magnesium (1.49%) increased at the application of lime (1.86 t ha^{-1}) with vermicompost (5 t ha^{-1}). The main effects also increased total nitrogen, available phosphorus, cation exchangeable capacity, and potassium, whereas significantly decreased exchangeable acidity and aluminum. The main and interaction effects of lime and vermicompost significantly improved yield and yield components of barley. The highest grain yield of 5097 kg ha^{-1} was recorded from the combined application of lime 1.86 t ha^{-1} and vermicompost 5 t ha^{-1}. Whereas, the lowest grain yield of 3635 kg ha^{-1} was recorded from the control. Overall, the combined application of organic fertilizer and lime amendments could be recommended to amend soil acidity and improve the availability of nutrients and crop yield. However, further research is needed to evaluate the long-term effects of both organic and lime amendments.

Keywords: Barley; grain yield; lime; soil acidity; vermicompost.

1. INTRODUCTION

"Soil acidity is the major cause of soil fertility depletion, which affects approximately 50% of the world's potentially arable soils" (Demil et al., 2020; Kochian et al., 2004). "It is a complex of numerous factors involving nutrient deficiencies and toxicities, low activities of beneficial microorganisms, and reduced plant root growth, which limits the absorption of nutrients such as phosphorus (P), calcium (Ca^{2+}), potassium (K^+), magnesium (Mg^{2+}), and molybdenum (Mo) and water" (Fageria and Baligar, 2008). "Acid soils are widespread and occupy 43% of the total cultivated land in Ethiopia" (Agegnehu et al., 2021; Agegnehu et al., 2019). In western highland parts of Ethiopia, agricultural production and productivity have been declining over time due to soil acidity and low soil fertility (Tamene et al., 2017; Zelleke et al., 2010).

"Increasing the pH of acidic soils via liming improves the availability of some nutrients to plants while reducing the exchangeable acidity" (Dereje et al., 2019; Megersa, 2020). "Vermicompost can restore and improve nutrients sustainably and has a high water-holding capacity, aeration, and high porosity compared to mineral fertilizer due to its humus content" (Meena, 2020; Sinha et al., 2010). Consequently, many parts of the Ethiopian highlands in general, Banja district in Awi zone in particular, have a problem of acidity which causes a gradual decline in soil fertility and crop productivity.

"Barley is the dominant cereal crop grown in the highlands of Ethiopia where soil acidity is rampant. Specifically, in areas with strong acidic soil (pH<5.5), the growth of crops is affected due to high concentrations of Aluminum (Al^{3+}) and manganese (Mn), resulting in the deficiency of available nutrients" (Agegnehu et al., 2019). The area coverage in barley is about 1.15 million ha, with a national average yield of 2.18 t ha^{-1} (CSA, 2021).

Soil acidity is one of the major bottlenecks to barley production in the highlands of Ethiopia (Moges et al., 2018). Thus, the management of soil acidity and fertility with organic fertilizer and lime amendments could be used as one of the most effective strategies to improve soil fertility and increase agricultural productivity. Although the problem of soil acidity has been well recognized, research on the effects of vermicompost and lime on acidic soils and barley yield is inadequate in barley-growing areas of northwestern Ethiopian highlands. Consequently, identifying effective soil fertility management methods through the combined application of organic fertilizers and lime is needed to amend soil acidity, replenish the soil macro and micro nutrients, and improve crop production and productivity in the study area. Therefore, the objectives of this study were initiated to 1) investigate the ameliorative effect of the separate and combined application of vermicompost and lime on soil acidity and soil physicochemical properties; and 2) evaluate the main and interaction effects of lime and vermicompost on growth and yield of barley in Banja district of northwestern Ethiopian highland.

2. MATERIALS AND METHODS

2.1 Description of the Study Area

2.1.1 Location

Geographically, the study area Sanketlideta kebele is located in Banja district, Awi administrative zone, Amhara National Reginal State, Northwest Ethiopia. Banja is located at 10˚47ˈ30″ to 11˚4ˈ0″N latitude and 36˚40ˈ0″ to 37˚10ˈ0″ E longitude. The soil type of the study area is Eutric Nitisol characterized by shallow, moderate to deep, very deep, and sandy clay-to-clay textural types (Fig. 1).

2.1.2 Climate

According to Bahr Dar Metrology Station of the National Meteorology Agency, the weather data indicated that the mean minimum and maximum temperatures of the study area from 2011 to 2020 were 12.98 and 26.26ºC, respectively. The mean annual rainfall was 1864.13 mm in the main wet season from June to September, with a less pronounced wet period up to November for the main growing season of crops (Fig. 2).

2.2 Experimental Procedure

The experiment was conducted in the representative acid soil-affected areas, using barley as a test crop, which is the major crop grown in the area. Different rates of limestone ($CaCO_3$) and vermicompost were used as experimental factors to ameliorate soil acidity with recommended mineral fertilizer. The treatments included factorial combinations of four rates of lime (0, 50%, 100%, and 150%) with the equivalent lime rates of 0, 0.93, 1.86, and 2.79 t ha^{-1} based on the exchangeable acidity and bulk density of the soil and three rates of vermicompost (0, 2.5, and 5 t ha^{-1}), with a total of 12 treatments. The experiment was laid out in a randomized complete block design with three replications. Hundred percent indicates the result that is gained from the lime requirement formula. The lime and vermicompost were applied a month before planting and incorporated into the 15 cm soil depth. Because lime takes enough time to react with the soil and neutralize acidity, vermicompost gradually release nutrients become available to plants. The mineral fertilizers applied uniformly to all plots were Urea and nitrogen, phosphorus, sulfur, and boron-containing blended fertilizer (NPSB). The recommended rate of inorganic fertilizers for barley is 200 kg ha^{-1} urea and 100 kg ha^{-1} NPSB. Urea was applied in two splits, i.e., half at sowing and half at knee height stage by considering the soil moisture condition, while the entire rate of NPSB was applied at sowing. High-yielding food barley variety HB 1307 was used as a test crop at a seed rate of 150 kg ha^{-1}. The total experimental area was 47m*13m, with a gross plot area of 3m*3m and a net plot area of 3m*2.6m. The spacing between rows, plots, and blocks were 0.2 m, 1 m, and 2 m, respectively. All cultural practices such as weeding were applied uniformly for all treatments and the crop was harvested when the crop reached physiological maturity, excluding the border rows.

The amount of lime required was calculated based on exchangeable Al^{3+} and H^+, the mass of soil per 15 cm hectare-furrow-slice and exchangeable Al^{3+} and H^+ of the study site as follows:

$$LR, CaCO_3\,(kg/ha) =$$

$$\frac{EA(kg/ha\ of\ soil * 0.15m * 10^4 m^2 B.D(g/cm^3) * 1000}{2000} \times 1.5 \qquad Eq\ (1)$$

Where, LR = Lime Requirement, EA = Exchangeable acidity, BD = Bulk density, 1.5 multiplication factor was adopted based on a recommendation by (Agumas et al., 2016).

2.3 Data Collection and Measurements

Soil samples were collected randomly from the surface layer of the experimental field at a depth of 0-15 cm. Initially, one composite soil sample was collected from the experimental site before lime and vermicompost application. Soil samples were also collected after harvesting the barley crop from each plot at a similar soil sampling depth. The collected samples were air dried, sieved to pass through 2 mm sieve, and prepared for the chemical and physical analysis of soil pH, exchangeable acidity, exchangeable Al^{3+}, organic carbon, total nitrogen, available phosphorus, cation exchange capacity, exchangeable bases, soil texture, and bulk density.

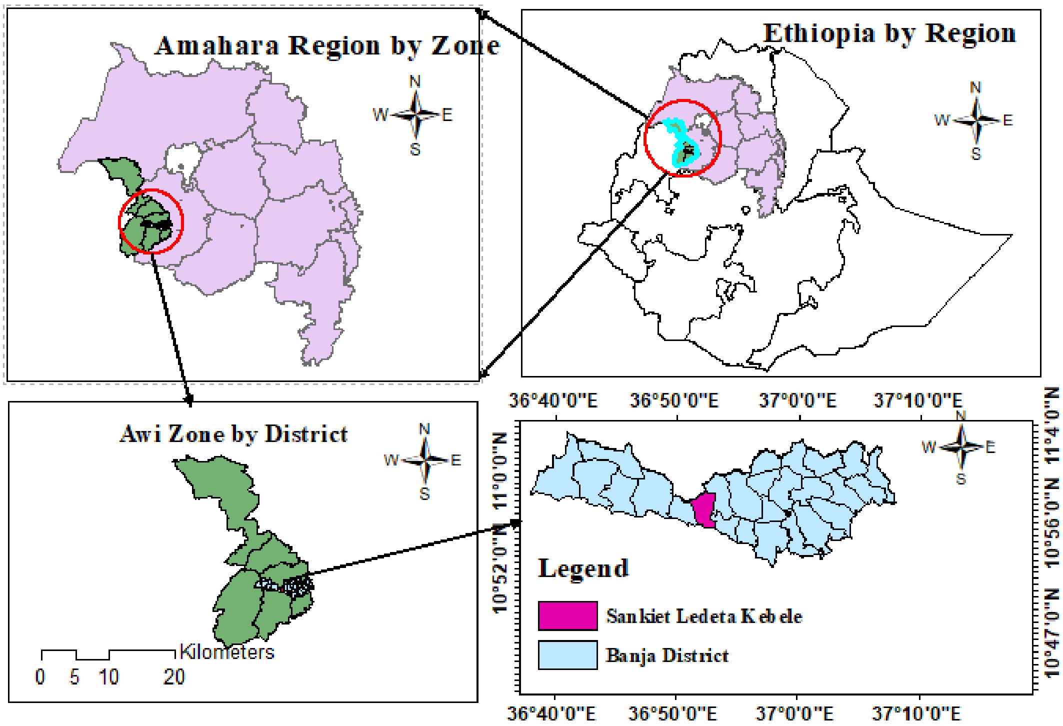

Fig. 1. Location map of the study area

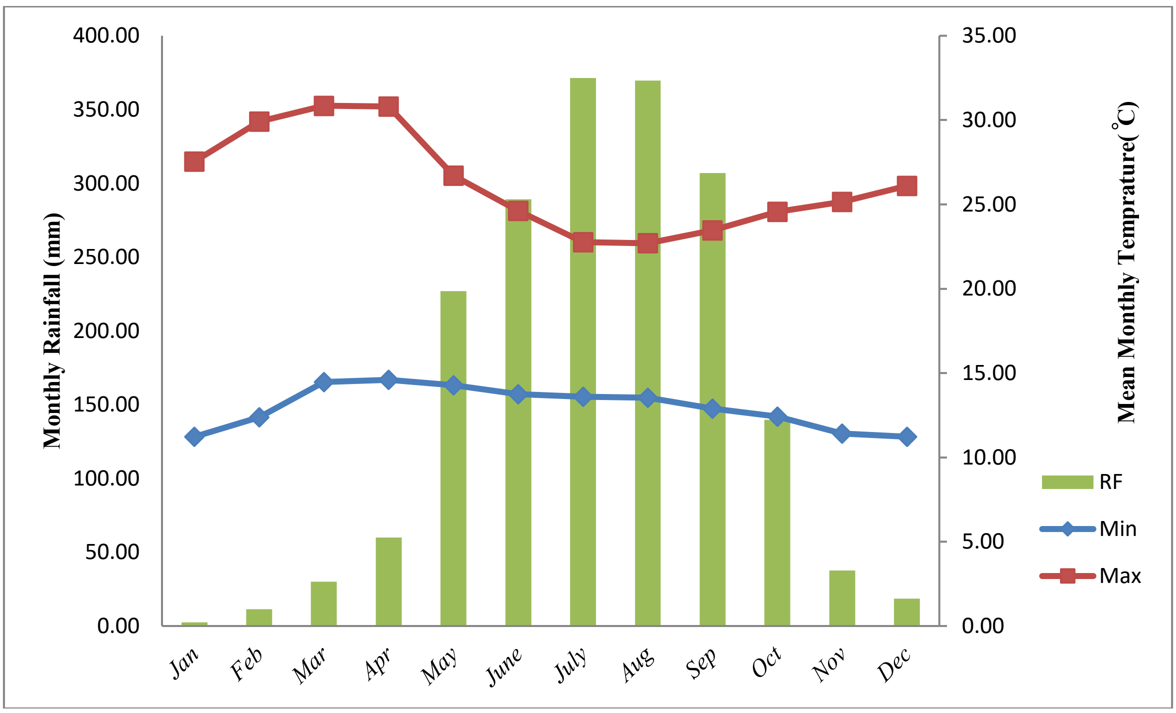

Fig. 2. Rainfall and temperature distributions (2011-2020) at the study area

Soil pH was measured potentiometrically using a digital pH meter with combined glass in the suspension of 1:2.5 soils to water ratio as described by (Carter and Gregorich, 2007). Soil organic carbon, total nitrogen (TN), and available P were determined by the Walkley-Black oxidation method (Walkley and Black, 1934), Kjeldahl digestion method (Bremner and Mulvaney, 1982), and standard Bray-II extraction methods (Bray and Kurtz, 1945), respectively.

Total P in soil samples was estimated by the Perchloric acid ($HClO_4$) digestion method as described by (Jackson, 1967).

Exchangeable acidity and exchangeable Al^{3+} were determined by saturating the soil samples with 1M KCl solution and the filtrate was titrated with 0.02M NaOH and 0.02M HCl, respectively as described by (Rowell, 1994). "The CEC was determined through distillation and titration of ammonia, after washing down excess ammonium acetate by ethyl alcohol (Sertsu and Bekele, 2000). Exchangeable bases (Ca^{+2}, Mg^{+2}, K^+, and Na^+) were determined using 1M neutral ammonium acetate (NH_4OAc) extraction method. In the extract, exchangeable Na^+ and K^+ were measured by using flame photometry, and exchangeable Ca^{2+} and Mg^{2+} were measured using atomic absorption spectrophotometry" (Rowell, 1994).

Soil particle size distribution was analyzed by the hydrometer method (Bouyoucos, 1962), using sodium hexametaphosphate (Calgon) as a dispersing agent. Soil textural class names were determined following the textural triangle system of the United States Department of Agriculture (USDA) as described by Rowell, (1994). "The bulk density of undisturbed cores is practical significance as it indicates soil aggregation and structure under field conditions. After 24 hours of oven drying, bulk density was calculated as the ratio of the weight of oven-dry soil to the volume of soil" (Blake, 1965).

Materials such as cow dung and straw (soybean, finger millet, and groundnut) were collected and chopped into small pieces using a cutter (sickle) and soaked in water for a week. This well-soaked straw material was at the bottom of the bin, followed by a thin layer of forest topsoil and then the cow dung was added. Then, the nationally well-known vermiworm (*Eisenia fetida*) was added to the top of the pit and covered with well-soaked straw. In each layer, water was sprinkled to maintain 70-80% moisture content of the prepared material. Finally, the vermicompost maturity was judged from 80 to 90 days visually by observing the formation of the granular structure of the compost at the surface of the tank. Finally, the vermicompost was separated from the vermiworm manually and stored at the optimum moisture content of 30-40% on average can be stored at the temperature of 18-25°C in a shade. The air-dried vermicompost was grounded and sieved to pass through two-millimeter sieve, and the chemical properties of the vermicompost such as total N, organic carbon, pH, and total P were analyzed following the standard procedures as described by Peters, (2003).

Data on growth, yield, and yield components of barley including number of effective tillers, spike length, plant height, number of grains per spike, aboveground total biomass, grain yield, straw yield, harvest index, and thousand-grain weight were collected. The grain quality parameters such as hectoliter weight and protein content were also measured. The total aboveground biomass and grain yield data collected on a plot basis were converted into per hectare after adjusting the grain yield to 12.5% moisture level for statistical analysis.

2.4 Statistical Analysis

All the collected agronomic and soil data were subjected to analysis of variance (ANOVA) using the general linear model (GLM) of SAS computer software version 9.4. The total variability for each trait was quantified using pooled analysis of variance over years based on the following model.

$$Y_{ijk} = \mu + R_i + L_j + VC_k + L * VC_{(ik)} + e_{ijk}$$

Where Y_{ijk} is total observation, μ = grand mean, R_i is the effect of the j^{th} replication, L_j is the effect of the j^{th} lime rate, VC_k is the effect of the k^{th} vermicompost rate, $L*VC_{(ik)}$ is the interaction and the e_{ijk} is the random error. Mean separation was done using the least significant difference (LSD) test at 5% probability level (SAS, 2013).

3. RESULTS AND DISCUSSION

3.1 Characterizing Vermicompost and Soil Properties before Treatment Application

The laboratory analysis of vermicompost indicated that the total nitrogen, organic carbon, P value, pH of vermicompost, and C:N ratios were described in Table 1. "The pH of vermicompost varies based on the types of raw materials used for vermicomposting. The C:N ratio is an important parameter commonly used to see the progress of organic material undergoing vermicomposting process and there is a distinct variation in C:N ratio depending on the starting organic material in the process" (Meena, 2020). "Nitrogen varies from 0.1% to 4% and can be increased further by manipulation of nitrogen rich starting material and is an important parameter in determining the quality of vermicompost in terms of usage for various crop production (Edwards and Bohlen, 1996). In the process of vermicomposting from the initial to the final stages, the content of organic carbon changes which is an important indicator of how the process proceeds and stabilization occurs" (Meena, 2020). The mature vermicompost when stabilized should have the optimum macronutrients like phosphates which are an indicator of quality. The concentration of phosphates in general should be more than 0.5%. It is necessary to specify the total content of P in finished vermicompost as it is an indication of the overall macronutrient value. Generally, a P content of more than 0.5% is desirable. Seedlings and plants which are sensitive to phosphates may require less than 0.1% (Edwards and Bohlen, 1996).

Before treatment application, the results of soil analysis indicated that the textural class of the soil was sandy clay loam, with a relative proportion of 28% clay, 12% silt, and 60% sand (Table 2). The weight of soil bulk density before lime and vermicompost application was moderate (1.37g cm^{-3}) (Hazelton and Murphy, 2007).

Soil pH of 4.80 was in the very strongly acidic soil range (Hazelton and Murphy, 2007). The total nitrogen and organic carbon content of the soil before applying lime and vermicompost were found to be medium (0.20%) and moderate (2.78%), respectively (Tadesse et al., 1991). The exchangeable acidity of the soil indicated the presence of higher Al^{3+} and H^+ ions in the soil colloid compared to the total cation exchange capacity (CEC) of the soil. The exchangeable acidity and Al^{3+} concentration of the experimental soil before the application of the treatments were 1.21 cmol $_{(+)}$ kg^{-1} and 1.12 cmol $_{(+)}$ kg^{-1}, respectively. The level of phosphorus for the experimental soil was low before application of the treatments (11.81 mg kg^{-1}) (Sertsu and Bekele, 2000). The results showed that the CEC of the experimental soil was 24.91 cmol $_{(+)}$ kg^{-1} that is moderate based on Hazelton and Murphy (2007) classification. The removal of basic cations, especially Ca^{2+} and Mg^{2+}, by leaching and erosion results in their replacement by acidic cations of H^+, Al^{3+} and Fe^{2+} on exchangeable sites and in the soil solution (Johnston, 2004). Soil analysis results indicated that exchangeable Ca^{2+}, Mg^{2+}, Na^+ and K^+ were 3.99, 0.33, 0.22, and 0.52 cmol $_{(+)}$ kg^{-1}, respectively, where According to classification, the levels of Ca^{2+}, Mg^{2+}, and Na^+ were low for the experimental soil, while K^+ was in the moderate range (Hazelton and Murphy, 2007).

Table 1. Selected chemical properties of vermicompost

Parameters	pH (1:2.5 H_2O)	OC (%)	OM (%)	TN (%)	CEC cmol $_{(+)}$ kg	TP (%)	C:N ratio
Value	8.45	10.69	18.44	1.66	65.59	0.61	6.44

pH=power of hydrogen, OC=organic carbon, OM=organic matter, TN=total nitrogen, CEC=cation exchange capacity, TP=total phosphorus, C:N ratio=carbon to nitrogen ratio

Table 2. Selected soil physicochemical properties before application of the treatments

Parameters	Unit	Value
Soil textural class		Sand clay loam
Sand	%	60
Silt	%	12
Clay	%	28
pH (H_2O)	1:2.5	4.8
Soil bulk density	g/cm^3	1.37
Total nitrogen (TN)	%	0.20
Organic carbon (OC)	%	2.78
Exchangeable Acidity	cmol $_{(+)}$/kg	1.21
Exchangeable Aluminum (Al^{3+})	Cmol $_{(+)}$/kg	1.12
Available Phosphorus (P)	mg/kg	11.81
Cation exchange capacity (CEC)	Cmol $_{(+)}$/kg	24.91
Exchangeable calcium (Ca^{2+})	Cmol $_{(+)}$/kg	3.99
Exchangeable magnesium (Mg^{2+})	Cmol $_{(+)}$/kg	0.33
Exchangeable sodium (Na^+)	Cmol $_{(+)}$/kg	0.22
Exchangeable potassium (K^+)	Cmol $_{(+)}$/kg	0.52

Table 3. The interaction effects of lime and vermicompost (VC) on soil pH and organic carbon (OC)

Lime(t/ha)	VC (t/ha)	pH (1:2.5 H_2O)	OC (%)
0	0	4.99[h]	2.73[d]
0	2.5	5.18[g]	2.95[bc]
0	5	5.20[g]	2.78[cd]
0.93	0	5.25[fg]	2.63[d]
0.93	2.5	5.42[bcd]	3.04[ab]
0.93	5	5.30[fe]	3.00[ab]
1.86	0	5.44[bc]	2.98[b]
1.86	2.5	5.36[cde]	3.05[ab]
1.86	5	5.46[b]	3.17[a]
2.79	0	5.35[de]	2.97[b]
2.79	2.5	5.46[b]	3.07[ab]
2.79	5	5.55[a]	3.05[ab]
Significance level		***	*
LSD (0.05)		0.08	0.17
SE±		0.03	0.29
CV (%)		0.79	3.21

***, * Significant at 0.001 and 0.05 probability levels, respectively.

3.2 Effects of Lime and Vermicompost on Soil Chemical Properties After Harvesting

The analysis of variance revealed that the main and interaction effects of lime and vermicompost were highly significant ($p<0.001$) for soil pH. The highest pH value of 5.55 was obtained from the combined application of 2.79 t/ha lime and 5 t ha^{-1} of vermicompost, while the lowest pH value of 4.99 was recorded from the control treatment (Table 3). The increase in soil pH might be due to the neutralization of H^+ and Al^{3+} ions because of the presence of Ca^{2+} and CO_3^{2-} contributed by the application of vermicompost and lime. Similarly, the application of lime either alone or in combination with vermicompost had a significant effect on soil pH (Bekele et al., 2018; Terefe et al., 2024). Vermicompost raises soil pH due to its moderate contents of basic cations and buffer capacity. Therefore, some nutrients like phosphorus become highly available to plants, and elements such as Al, Mn, and Fe are reduced" (Negese et al., 2021).

The application of lime at different rates raised soil pH close to the optimum requirement of barley, but radically decreasing the exchangeable Al^{3+} to a minimum level of 0.1 cmol $_{(+)}$ kg^{-1} and decreased soil acidity level, thereby enhanced the available phosphorus in the soil. When lime is added to acid soils containing high Al^{3+} and H^+ concentrations, it dissociates into Ca^{2+} and OH^- ions. The hydroxyl ions react with hydrogen and Al^{3+} ions forming Al^{3+} hydroxide and water, thereby increasing soil pH in the soil solution (Agegnehu et al., 2019; Desalegn et al., 2017). The main and interaction effects of lime and vermicompost significantly increased soil organic carbon. The highest soil OC content of 3.17% was obtained from the application of 1.86 t ha^{-1} lime and 5 t ha^{-1} vermicompost, while the lowest soil OC content of 2.73% was recorded from the control treatment (Table 3). The findings of a similar study indicated that the application of organic fertilizer significantly improved soil organic carbon from 1.26% to 1.56% (Chala et al., 2020).

The application of lime ($p<0.05$) and vermicompost ($p<0.001$) showed a significant effect on the total N content of the soil, but the interaction effect of lime and vermicompost was not significant on soil N content. The highest total nitrogen values of 0.24% and 0.23% were obtained from the application of 2.79 t ha^{-1} and 1.86 t ha^{-1} lime, respectively, while the lowest total soil N content of 0.22% was recorded from the control (untreated) plots (Table 4). The increase in soil N due to the application of lime might be owing to the mineralization of the nutrients and the direct relation of soil water pH and OC. The addition of lime to acidic soil improves the soil environment for plant growth by increasing soil pH. A more favorable root environment may be a result of desirable soil pH, decreasing the toxicity of Al^{3+} and Mn^{3+}, increasing Ca^{2+} and Mg^{2+} supplies, and enhancing the availability of P and Mo (Takala, 2018). Liming increased the content of TN which may be associated with the addition of a high amount of organic inputs from crop residues and plant roots (Antoniadis et al., 2015). Similarly, the highest total soil N content of 0.24% was obtained from the application of 5 t ha^{-1} vermicompost, while the lowest total soil N content of 0.21% was recorded from the control treatment, which might be due to the residual effects of vermicompost. According to (Bekele et al., 2018), the application of vermicompost on acidic soil increases the organic matter and total nitrogen contents of the soil. The application of organic fertilizers significantly improved soil nitrogen from 0.14% to 0.23% on Nitisols of central Ethiopian Highlands (Chala et al., 2020). "The separate or combined application of lime and vermicompost increased the mineralization of nitrogen" (Chimdessa, 2021).

The main effect of lime ($p<0.001$) and vermicompost ($p<0.05$) significantly decreased soil exchangeable acidity and Al^{3+}, but their interaction effect was not significant (Table 4). Accordingly, the application of 2.79 t ha^{-1} lime lowered the soil exchangeable acidity by 69.6% and aluminum by 70.9% compared to the control. Exchangeable acidity decreased with increasing lime rate, which might be associated with the increase in the soil pH due to the replacement of H^{+} and Al^{3+} by Ca^{2+} ions from lime on the soil colloids. The result is consistent with the findings of Chimdessa, (2021) who reported that exchangeable acidity was significantly reduced due to different lime rates. Similarly, integrated application of lime and vermicompost decreased exchangeable acidity (Terefe et al., 2024). Desalegn et al., (2017) reported that the application of lime and its residual effect highly decreased exchangeable aluminum from the initial level of 1.32 to 0.12 Cmol $_{(+)}$ kg^{-1} as the level of applied lime rates increased. Similarly, the exchangeable acidity was significantly ($p<0.05$) decreased by 1.77% and 20.9% after the application of 2.5 and 5 t ha^{-1} vermicompost (VC), respectively. Likewise, the level of exchangeable Al^{3+} declined by 10.6 and 21.97% after the application of 2.5 and 5 t ha^{-1} of VC, respectively (Table 4), indicating that the increase in the VC application rates resulted in the decline in soil exchangeable acidity and Al^{3+} due to the increase in soil pH as well as the improvement in the available nutrients. The application of lime alone or in combination with vermicompost had a significant ($p<0.001$) effect on soil exchangeable acidity and aluminum (Bekele et al., 2018).

The main effect of lime ($p<0.01$) and vermicompost was significant ($p<0.05$) on the availability of phosphorus, but their interaction effect was not significant (Table 4). The highest available P (16.49 mg kg^{-1}) was recorded from the application of 1.86 t lime ha^{-1}, while the lowest available P (12.69 mg kg^{-1}) was recorded from the control treatment. In soils high in exchangeable acidity, liming could decrease Al^{3+} and increase phosphorus uptake by plants. Therefore, liming materials added to the soil could improve soil nutrients and it hydrolyzes Al^{3+} and Fe^{2+} ions that precipitated with P. Hence, the precipitated phosphate ion is released into the soil solution thereby rendering the phosphate ion available for plant uptake. Thus, liming raises the pH of acidic soil and provides more favorable environments for microbial activities and possibly results in the net mineralization of soil organic phosphorus. It can increase phosphate availability by stimulating the mineralization of soil organic phosphorus (Ameyu, 2019; Kisinyo, 2016). Vermicompost application also increased the availability of phosphorus compared with the control treatment. The highest available P (15.54 mg kg^{-1}) was obtained from the application of 5 t VC ha^{-1}, while the lowest (13.27 mg kg^{-1}) was recorded from the control treatment. The high amount of phosphorus in Vermicompost is the main cause for the marked increase in the availability of phosphorus for plant growth. The application of organic fertilizer significantly improved soil phosphorous from 7.84 mg kg^{-1} to 12.59 mg kg^{-1} on Nitisols of Central Ethiopian Highlands (Chala et al., 2020). "Phosphorus is commonly bound to iron and Aluminum oxides and hydroxides through chemical precipitation or physical adsorption which improves phosphorus mineralization from organic matter" (Terefe et al., 2024).

The analysis of variance showed that the main effect of lime and vermicompost significantly ($p<0.01$ and $p<0.05$) influenced soil cation exchange capacity, but their interaction effect did not have a significant difference on soil CEC (Table 4). The highest CEC value of 29.95 cmol $_{(+)}$ kg^{-1} was obtained from the application of 1.86 t ha^{-1} lime, which was at par with 2.79 t ha^{-1} and 0.93 t ha^{-1} lime, and the lowest CEC value of 27.68 cmol $_{(+)}$ kg^{-1} was recorded from the control treatment. The increase in CEC due to liming could be attributed to the change in pH and the release of the interlayer substitutional negative charge by deprotonation of the variable charge minerals and functional groups of humic compounds caused by Ca^{2+}. The greater amount of negative charge available on the surfaces of these minerals increases CEC. Liming acidic soil indirectly increases the effective cation exchange capacity of soils that contain organic matter or variably charged clay minerals (Buni, 2014). Similarly, the application of 5 t ha^{-1} vermicompost resulted in the highest (29.42 cmol $_{(+)}$ kg^{-1}) CEC, while the lowest (28.21 cmol $_{(+)}$ kg^{-1}) was recorded from the control treatment. However, it contradicts the result of Chimdessa, (2021) where the change in soil CEC due to lime and vermicompost application is minimal and statistically insignificant. It might be due to the addition of lime and vermicompost which facilitates organic matter decomposition that may decrease soil CEC.

The main effect of lime had a significant ($p<0.05$) effect on the soil potassium, whereas the main effect of vermicompost and the interaction effect of lime with vermicompost were nonsignificant on soil potassium content. The highest (1.09 cmol $_{(+)}$ kg^{-1}) soil K^+ was obtained from the application of 2.79 t ha^{-1} lime, while the lowest K value of 0.64 cmol $_{(+)}$ kg^{-1} was recorded from the control treatment without lime (Table 4). According to Bekele et al., (2018), the availability of exchangeable bases (Ca^{2+}, Mg^{2+}, Na^+ and K^+) was increased due to the application of lime, which might be attributed to the increase in soil pH.

Table 4. The main effects of lime and vermicompost on total nitrogen, exchangeable acidity and aluminum, available phosphorus (P), cation exchange capacity (CEC) and potassium (K)

Lime (t/ha)	Total N (%)	Ex. Acidity (Cmol $_{(+)}$ kg^{-1})	Ex. Al^{3+} (Cmol $_{(+)}$ kg^{-1})	Av. P	CEC	Ex. K
0	0.22^{b}	1.50^{a}	1.00^{a}	12.69^{c}	27.68^{b}	0.64^{b}
0.93	0.23^{ab}	0.89^{b}	0.62^{b}	14.10^{bc}	29.03^{a}	0.85^{b}
1.86	0.23^{a}	0.69^{c}	0.47^{c}	16.49a	29.95a	0.84^{b}
2.79	0.24^{a}	0.46^{d}	0.29^{d}	15.58^{ab}	29.47^{a}	1.09^{a}
Significance level	*	***	***	**	**	**
LSD (0.05)	0.01	0.18	0.12	2.01	0.96	0.22
Vermicompost (t/ha)						
0	0.21^{c}	0.96^{a}	0.67^{a}	13.27^{b}	28.21^{b}	0.73
2.5	0.23^{b}	0.94^{a}	0.60^{ab}	15.34a	28.72^{ab}	0.89
5	0.24^{a}	0.76^{b}	0.52^{b}	15.54^{a}	29.42^{a}	0.95
Significance level	***	*	*	*	*	NS
LSD (0.05)	0.012	0.15	0.10	1.74	0.83	0.19
SE±	0.003	0.07	0.05	0.43	0.22	0.05
CV (%)	6.79	20.78	20.93	13.02	3.65	25.8

****, **, * Significant at 0.001, 0.01, and 0.05 probability levels, respectively; NS: Non- significant.*

Table 5. The interaction effects of lime and vermicompost on soil exchangeable calcium (Ca), magnesium (Ma) and sodium (Na)

Lime(t/ha)	VC (t/ha)	Exch. Ca	Exch. Mg	Exch. Na
0	0	4.34^{f}	0.31^{e}	0.19^{c}
0	2.5	4.78^{ef}	0.32^{e}	0.20^{c}
0	5	6.75^{de}	1.35^{ab}	0.46^{ab}
0.93	0	4.97^{ef}	0.68^{de}	0.48^{ab}
0.93	2.5	8.05^{cd}	1.47^{a}	0.45^{b}
0.93	5	8.76^{bcd}	1.07^{bc}	0.49^{ab}
1.86	0	10.05^{bc}	1.39^{ab}	0.47^{ab}
1.86	2.5	9.99^{bc}	1.39^{ab}	0.47^{ab}
1.86	5	10.45^{b}	1.49^{a}	0.49^{ab}
2.79	0	5.37^{ef}	0.73^{cd}	0.49^{ab}
2.79	2.5	10.75^{b}	1.34^{ab}	0.47^{ab}
2.79	5	14.36^{a}	1.43^{ab}	0.58^{a}
Significance level		**	***	*
LSD (0.05)		2.34	0.39	0.12
SE±		0.53	0.08	0.02
CV (%)		16.99	21.51	15.78

****, **, * Significant at 0.001, 0.01, and 0.05 probability levels, respectively.*

The analysis of variance revealed that exchangeable soil calcium, magnesium, and sodium were highly significantly ($p<0.001$) influenced by the interaction effects of lime and vermicompost (Table 5). The highest (14.36 cmol $_{(+)}$ kg^{-1}) exchangeable calcium was measured from the application of 2.79 t ha^{-1} lime and 5 t ha^{-1} vermicompost, while the lowest (4.34 cmol $_{(+)}$ kg^{-1}) exchangeable Ca was recorded from the control plot. Similarly, the highest (1.49 and 1.47 cmol $_{(+)}$ kg^{-1}) exchangeable soil magnesium values were recorded from the application of 1.86 t ha^{-1} lime and 5 t ha^{-1} vermicompost, followed by 0.93 t ha^{-1} lime and 2.5 t ha^{-1} vermicompost, respectively.

The lowest (0.31 cmol $_{(+)}$ kg^{-1}) exchangeable Mg^{2+} was recorded from the control treatment. The highest (0.58 cmol $_{(+)}$ kg^{-1}) exchangeable sodium was obtained from the application of 2.79 t ha^{-1} lime and 5 t ha^{-1} of vermicompost, while the lowest exchangeable Na^{+} values of 0.19 and 0.20 cmol $_{(+)}$ kg^{-1} were recorded from the control and 0 lime with 2.5 t ha^{-1} vermicompost, respectively. Similarly, Kisinyo, (2016) reported that the application of lime to acidic soils increased Ca^{2+} and/or Mg^{2+} ions and reduced Al^{3+}, H^{+}, Mn^{2+}, and Fe^{2+} ions in the soil solution. Soil calcium and magnesium were markedly increased by the application of lime and vermicompost. Increasing lime with vermicompost application rates increased soil calcium and magnesium concentrations.

3.3 Effects of Lime and Vermicompost on Growth, Yield and Yield Components of Barley

The analysis of variance showed that the main effect of lime and vermicompost significantly ($p<0.001$ and $p< 0.05$) increased the number of effective barley tillers m^{-2}, while the interaction effect of lime and vermicompost was non-significant for effective tiller numbers m^{-2} (Table 6). The highest effective tiller numbers (447.56 m^{-2}) were obtained from the application of 2.79 t ha^{-1} lime. However, it was at par with the 1.86 t ha^{-1} lime rate which recorded 435.78 tillers m^{-2}, with a 34.8% increase in the number of tillers m^{-2} over the control treatment. Bore and Bedadi, (2016) reported that the highest number of tillers was recorded from lime-treated soil, which agrees with the finding of Desalegn et al. (2017) where the highest number of tillers was recorded in the lime-amended plots. Similarly, the application of 5 t ha^{-1} vermicompost resulted in the highest mean effective tiller numbers (428.83), with an increase in the number of effective tillers by 10.29% compared to the control, while the lowest number of effective tillers (388.83) was obtained from the control treatment.

The main effect of lime and vermicompost was significant ($p<0.01$ and $p<0.05$) for barley spike length, but the interaction effect of lime and vermicompost was not significant for this parameter (Table 6). The maximum spike length (6.1 cm) was recorded from the application of 1.86 t ha^{-1} lime, which was at par with 2.79 t ha^{-1} and 0.93 t ha^{-1} of lime, while the smallest mean spike length (5.64 cm) was recorded from the control treatment. The spike length was significantly increased with the application of lime up to the optimum level. The increase in spike length with increasing lime rates on acidic soils is highly likely related to the increase in the concentration of exchangeable cations and soil fertility and the reduction of the toxic concentration of Al and H. In line with this result, the application of different rates of agricultural lime significantly improved the spike length of wheat (Kamaruzzaman et al., 2013). Likewise, the maximum (6.08 cm) spike length was recorded from the application of 5 t ha^{-1} vermicompost, whereas the lowest spike length of 5.78 cm was recorded from 2.5 t ha^{-1} vermicompost (Table 6). The application of organic and inorganic nutrient sources either alone or in combination significantly improved the spike length of barley (Agegnehu et al., 2016; Chala et al., 2020).

The analysis of variance revealed that the plant height of barley was significantly affected ($p<0.05$) by the main effect of VC, lime and their interaction (Table 7). The combined application of 1.86 t ha^{-1} lime and 5 t ha^{-1} of vermicompost recorded the tallest plant height (108.61 cm), but it was at par (108.01 cm) with 2.79 t ha^{-1} lime and 5 t ha^{-1} VC rate, while the shortest plant height (96.61 cm) of barley was recorded from the control treatment (Table 7). The significant barley plant height increment in response to the increasing lime rates on acidic soils over the control could be because of the lime's ability to neutralize soil acidity and the reduction of its toxicity effect on plant growth and the subsequent increase in soil nutrient availability by enhancing mineralization. Liming might have reduced the detrimental effect of soil acidity on plant growth due to the high concentration of H^{+} and Al^{3+} ions in the acidic soil. Similarly, the combined application of integrated organic and inorganic fertilizers was highly significant (p<0.01) for plant height of food barley (Ameyu, 2019; Chala et al., 2020; Chimdi et al., 2012).

The main and interaction effect of lime and vermicompost was highly significant (p<0.001) for the number of grains per spike (Table 7). The highest number of grains per spike (36.83) was recorded from the combined application of 1.86 t ha^{-1} lime and 5 t ha^{-1} vermicompost, whereas the lowest number of grains per spike (28.47) was recorded from the untreated (control) treatment. The potential of barley spike is determined by the number of grains $spike^{-1}$ which is an important yield component of grain yield. The number of grains per spike, which depends on the spike length, was increased due to the application of optimum lime rate and high rate of vermicompost. This indicates that the combined use of lime with vermicompost may increase the available nutrients like nitrogen, phosphorus, potassium, soluble calcium, nitrate (NO_3^-) and other necessary elements for plant growth and the reduction of toxic concentrations of aluminum and hydrogen.

The analysis of variance showed that the main and interaction effect of lime and vermicompost application had a significant (p<0.01) effect on grain yield of barley (Table 7). The maximum grain yield of 5097 kg ha^{-1} was obtained from the application of 1.86 t ha^{-1} lime with 5 t ha^{-1} vermicompost, while the minimum grain yields of 3635 and 3713 kg ha^{-1} were recorded from control and 0 lime with 2.5 t ha^{-1} vermicompost, respectively. Grain yield is the result of other parameters and the application of optimum lime rate with high vermicompost increased barley grain yield, which might be due to the reduction of toxicity of Al^{3+} and H^+ ions and the increase in the available nutrients. The trend in grain yield increase was related to plant height, spike length, and seed number per spike. A similar study has also shown that the combined application of organic and inorganic fertilizers was highly significant (p<0.01) for grain yield of food barley (Chala et al., 2020). The increase in crop yield through the application of lime may be attributed to the neutralization of Al^{3+} and increased availability of plant nutrients. Lime raised soil pH which could lead to the increased availability of soil P by unlocking the P fixed by the soil into available P for crop use and basic cations, especially calcium which forms plant structure (Desalegn et al., 2017; Nadir et al., 2015).

The main effects of lime and the interaction effect of lime and vermicompost were significant (p<0.05) for thousand-grain weight (TGW), while the main effects of vermicompost was not significant. The maximum thousand-grain weight (53.72 g) was obtained from the combined application of 2.79 t ha^{-1} lime and 5 t ha^{-1} vermicompost, while the minimum TGW (50.09 g) was recorded from the control treatment (Table 7). The finding of a similar study indicated that the combined application of lime and P had a significant (p<0.05) effect on the thousand-grain weight of barley (Moges et al., 2018). Kamaruzzaman et al., (2013) also reported that liming had significant effects on the thousand-grain weight of wheat. The integrated application of organic and inorganic fertilizers was significant for the thousand-grain weight of barley (Agegnehu et al., 2016).

Table 6. The main effects of lime and vermicompost on spike length (SL) and number of effective tillers (ETM) per meter square

Lime rate (t/ha)	SL (cm)	ETM^{-2}
0	5.64^b	353.11^b
0.93	5.99^a	378.67^b
1.86	6.10^a	435.78^a
2.79	5.99^a	447.56^a
Significance level	**	*
LSD (0.05)	0.24	36.28
Vermicompost (t/ha)		
0	5.93^{ab}	388.83^b
2.5	5.78^b	393.67^b
5	6.08^a	428.83^a
Significance level	*	*
LSD (0.05)	0.21	31.42
SE±	0.05	9.22
CV (%)	4.05	8.36

***, * Significant at 0.01 and 0.05 probability levels, respectively.*

The analysis of variance showed that the interaction effect of lime and vermicompost was significant ($p<0.05$) for straw yield of barley. The highest straw yield of 7541.7 kg ha^{-1} was obtained from the combined application of the highest lime rate of 2.79 t ha^{-1} and 5 t VC ha^{-1}, while lower straw yields of 5434, 5523, and 5403 kg ha^{-1} were recorded from the control (untreated), 0-2.5, and 0-5 lime-VC t ha^{-1}, respectively (Table 7). The application of 4- and 6 t lime ha^{-1} increased straw yield by 22.59% and 22.96% compared to the control (Moges et al., 2018). According to Agegnehu et al., (2016), the application of organic materials on the soil significantly ($p<0.01$) improved straw yields of barley.

The analysis of variance showed that the harvest index (HI) of barley was significantly ($p<0.01$) influenced by the interaction effect of lime and vermicompost as well as the main effect of vermicompost rates. However, the sole application of lime did not affect the harvest index of barley (Table 7). The combined application of 1.86 t ha^{-1} lime and 5 t ha^{-1} vermicompost gave the highest HI (45.16%), while the lowest HI of 39.67% was obtained from the application of 2.79 t ha^{-1} lime and 5 t ha^{-1} vermicompost, which might be due to high amount of lime and vermicompost that led to high vegetative growth and biomass, and hence low HI due to low grain yield and total biomass ratio. The highest harvest index was obtained from the application of high amount of vermicompost and lime (Abebe et al., 2024).

The main effect of vermicompost and the combined application of lime and vermicompost was significant ($p<0.01$) for the grain protein content of barley (Table 7). The grain protein content of barley ranged from 8.05% to 9.04%, where the protein content is mainly related to the level of soil nitrogen available to the plant and the type of crop variety. Grain protein content is an important quality component of cereals (Xu et al., 2012). Since food barley is a major source of protein in the highland areas of Ethiopia, increasing grain yield and quality of barley is important for food and nutrition security. The highest grain N concentrations attained (1.69% at Holetta and 1.58% at Robgebeya) are equivalent to the respective grain protein contents of 9.9% and 9.1%, respectively (Agegnehu et al., 2016). Liming increases the availability of cations which act as catalysts in protein synthesis. The content of protein after the physiological maturity stage was lower than after harvest, which explained that at grain filling stages the plants were still actively absorbing nitrogen from the soil. The amount of available soil nitrogen, soil moisture status, and temperature conditions determine the level of grain protein. High rates of nitrogen and limited soil moisture result in a protein content above acceptable malting level for malting barley (Nadir et al., 2015).

The ANOVA revealed that the main effect of lime and vermicompost were highly significant ($p<0.01$) for barley hectoliter weight (HLW), while their interaction was non-significant (Table 8). Accordingly, the highest hectoliter weight (629.3 g/l) was obtained from the application of 2.79 t ha^{-1} lime, but it was at par with 1.86 t ha^{-1} and 0.93 t ha^{-1} lime. The lowest (606.1 g/l) hectoliter weight was recorded from the control treatment. The result showed that the hectoliter weight increased as the lime rate increased from 0.93 to 2.79 t ha^{-1}. Desalegn et al., (2017) also reported that all the liming treatments had higher mean HLW values relative to the control (un-limed) treatment. Similarly, the analysis of hectoliter weight showed that the application of 5 t ha^{-1} of vermicompost gave the highest (629.1 g/l) hectoliter weight, while the control treatment gave the lowest HLW of 611.2 g/l, which might be due to the content of high organic matter and nutrients in the vermicompost.

The analysis of variance showed that the interaction effect of lime rates and vermicompost had no significant effect on the aboveground total biomass. In contrast, the main effects of lime and vermicompost were highly significant ($p<0.001$) for the total biomass of barley (Table 8). The highest barley total biomass of 11759 kg ha^{-1} was obtained from the application of 2.79 t ha^{-1} lime, while the lowest total biomass of 9319 kg ha^{-1} was recorded from the control (zero treatment). The increase in the total biomass of barley due to liming of acidic soils may be attributed to the reduction in H^+ and Al^{3+} ions and the increase in the availability of Ca^{2+} and P by raising soil pH. Chimdi et al., (2012) also reported that increasing lime application on acidic soil significantly increased the total biomass of barley. Similarly, the highest total biomass (11174) kg ha^{-1} was recorded from the application of 5 t ha^{-1} of vermicompost, while the lowest mean total biomass of 10608 kg ha^{-1} was recorded from the control treatment. The combined application of organic and inorganic fertilizers was highly significant ($p<0.01$) for the total biomass of food barley (Chala et al., 2020).

Table 7. The interaction effect of lime and vermicompost on yield and yield components of barley

Lime (t/ha)	VC	PH (cm)	NSPS	GY (kg/ha)	SY (kg/ha)	HI (%)	TGW (g)	Protein (%)
0	0	96.61^{d}	28.47^{e}	3635.4^{g}	5434.0^{c}	40.18^{de}	50.09^{d}	8.16^{cd}
0	2.5	103.40^{bc}	29.03^{de}	3713.4^{g}	5522.7c	40.21^{de}	51.59^{bc}	8.62^{ab}
0	5	100.09^{cd}	29.07^{de}	4250.0^{f}	5402.8^{c}	44.08^{ab}	50.87^{cd}	8.17^{cd}
0.93	0	103.26^{bc}	29.07^{de}	4548.6^{de}	6423.6^{b}	41.45^{cde}	51.93^{bc}	8.51^{bc}
0.93	2.5	102.33^{bc}	32.10^{bc}	4538.2^{de}	6225.7^{b}	42.18^{bcd}	51.70^{bc}	8.52^{bc}
0.93	5	106.04^{ab}	32.93^{b}	4888.9^{bc}	6362.5^{b}	43.49^{abc}	51.07^{bcd}	8.47^{bcd}
1.86	0	102.16^{c}	31.67^{bc}	4744.5^{dc}	6436.1^{b}	42.45^{bcd}	51.89^{bc}	8.05^{d}
1.86	2.5	101.76^{c}	30.73^{cd}	4457.3^{ef}	6445.5^{b}	40.88^{de}	52.20^{b}	9.04^{a}
1.86	5	108.61^{a}	36.83^{a}	5097.5^{a}	6194.1^{b}	45.16^{a}	51.95^{bc}	8.14^{cd}
2.79	0	102.55^{bc}	32.37^{bc}	4864.0^{bc}	6386.0^{b}	43.24^{abc}	51.07^{bcd}	8.55^{bc}
2.79	2.5	105.98^{ab}	32.57^{bc}	4791.7^{bc}	6736.1^{b}	41.60^{cde}	51.78^{bc}	8.26^{cd}
2.79	5	108.01^{a}	33.50^{b}	4958.3^{ab}	7541.7^{a}	39.67^{e}	53.72^{a}	8.37^{cd}
Significance level		*	**	**	*	**	*	**
LSD (0.05)		3.74	2.10	208.44	554.95	2.33	1.25	0.43
SE±		0.63	0.43	77.65	107.15	0.34	0.18	0.06
CV (%)		2.17	4.09	2.59	5.36	3.36	1.50	3.00

***, * Significant at 0.01 and 0.05 probability levels, respectively. VC=vermicompost, PH=plant height, NSPS=number of seeds per spike, GY=grain yield, SY=straw yield, HI=harvest index, TGW=thousand grain weight*

Table 8. The main effects of lime and vermicompost on total biomass yield (BY), and hectoliter weight (HLW) of barley

Lime rate (t/ha)	BY (kg/ha)	HLW (g/l)
0	9319.4[c]	606.1[b]
0.93	10995.8[b]	619.2[a]
1.86	11125.0[b]	624.4[a]
2.79	11759.3[a]	629.3[a]
Significance level	***	**
LSD (0.05)	378.78	12.31
Vermicompost (t/ha)		
0	10618.1[b]	611.2[b]
2.5	10607.6[b]	619.1[ab]
5	11174.0[a]	629.1[a]
Significance level	**	**
LSD (0.05)	328.03	10.66
SE±	170.03	2.73
CV (%)	3.48	2.12

****, **, Significant at 0.001 and 0.01 probability levels, respectively.*

Table 9. Relation between grain yield of barley and selected soil properties

Parameters	GY	pH	TN	OC	Ex. Acidity	Ex. Al^{3+}	Av. P	CEC	Ex. Ca	Ex. Mg	Ex. Na
pH	0.85***										
TN	0.74**	0.85***									
OC	0.57*	0.75**	0.78**								
Ex. acidity	-0.94***	-0.91***	-0.73**	-0.69**							
Ex. Al^{+3}	-0.90***	-0.93***	-0.76**	-0.71**	0.99***						
Av. P	0.65*	0.80**	0.75**	0.86***	-0.72	-0.73**					
CEC	0.87***	0.78**	0.83 ***	0.72**	-0.85***	-0.85***	0.65*				
Ex. Ca	0.68*	0.84***	0.90***	0.70*	-0.73**	-0.80**	0.71**	0.74**			
Ex. Mg	0.69**	0.79***	0.85***	0.61*	-0.64*	-0.69**	0.68*	0.72**	0.81***		
Ex. Na	0.91***	0.80***	0.72**	0.37NS	-0.81***	-0.81***	0.47NS	0.77**	0.67*	0.77**	
Ex. K	0.59*	0.69*	0.69*	0.50NS	-0.68*	-0.75**	0.45NS	0.70**	0.83***	0.48NS	0.61*

, **, * Significant at p≤0.05,0.01,0.001 probability level: NS: Not significant. GY= grain yield, pH=power of hydrogen, TN=total nitrogen, OC=organic carbon, Ex. acidity=exchangeable acidity, Ex. Al^{3+}=exchangeable aluminum, Av. P=available phosphorus, CEC=cation exchange capacity, Ex. (Ca, Mg, Na, K) = exchangeable (calcium, magnesium, sodium and potassium).*

3.4 Correlation between Grain Yield of Barley and Selected Soil Properties

Grain yield in cereals is the product of optimum soil nutrients. The correlation indicates that grain yield was strongly significantly ($p<0.001$) and positively correlated with soil pH ($r = 0.85$), TN ($r = 0.74$), CEC ($r = 0.87$), Mg ($r = 0.69$), and Na ($r = 0.91$). Grain yield was also significantly ($p<0.05$) and positively correlated with OC ($r = 0.57$), Ca ($r = 0.68$) and K ($r = 0.59$). On the other hand, grain yield was highly significant ($p<0.001$) and negatively correlated with exchangeable acidity ($r = -0.939$) and exchangeable Al ($r = -0.90$). Increasing soil pH also increases grain yield and decreases exchangeable acidity and Al^{3+}(Table 9), which may indicate that grain yield and available nutrients had direct relationship and invers relation with toxic nutrients. A similar finding by (Alemu et al., 2017) indicated barley grain yield was significantly ($P < 0.01$) positively correlated with some soil properties such as soil pH and available P, but significantly ($P<0.01$) negatively correlated with exchangeable acidity and Al^{3+}.

4. CONCLUSION AND RECOMMENDATION

Based on the results of the study, the application of lime and vermicompost significantly increased soil pH, total N, OC, available P, CEC, exchangeable Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}. This implies that the application of lime and vermicompost significantly decreased soil acidity and improved soil fertility and nutrient availability. Barley grain yield and yield components of barley were significantly increased due to the improvement of soil fertility and availability of nutrients in the amended acid soil. The main and interaction effects of lime and vermicompost significantly improved yield and some yield components of barley. The combined application of lime at 1.86 t ha^{-1} rate and the highest rate of 5 t ha^{-1} vermicompost improved soil fertility and yield of barley. Overall, the integrated use of lime with organic fertilizer could ameliorate soil acidity, improve soil nutrients, and increase yield of barley compared to the separate use of these amendments. From this study, despite being only one-season study results, the integrated application of lime at the rate of 1.86 t ha^{-1} and vermicompost at the rate of 5 t ha^{-1} was found to be optimum rates which could be recommended to reclaim soil acidity and improve soil fertility for improved growth and yield of barley. Further research is also needed to investigate the main and interaction effects of three factors, including organic and mineral fertilizers, and lime on acidic soils to improve soil fertility and determine the requirement of inorganic fertilizer for increased and sustainable barley yield.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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