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Research Article

Soil Properties, Crop Yield, and Economic Return in Response to Lime Application on Acidic Nitisols of Southern Highlands of Ethiopia

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Soil acidity is one of the major crop production constraints in the highlands of Ethiopia. Liming is becoming a common practice to amend soil acidity, but its effects on soil properties, crop yield, and farm income are not well studied. In this study, an on-farm liming experiment was conducted for two consecutive years (2020-2021) on acidic Nitisols (pH < 5.5) in Southern Ethiopia. The experiment consisted of six liming rates (control, 2.74, 4.11, 5.48, 6.85, and 8.22 $t{\cdot}ha^{-1}$) laid out in a randomized complete block design with three replications. Soil, agronomic, and economic data were collected in 2020 and 2021 cropping seasons and analyzed. The application of lime in the ranges of 2.74–8.22 $t{\cdot}ha^{-1}$ increased soil pH by 0.46–1.25 units and reduced exchangeable acidity by 2.02–3.17 units. Higher lime rates of 6.85–8.22 $t{\cdot}ha^{-1}$ increased soil pH sharply from 5.22 to 5.99 and 6.46, respectively, but such a rise in soil pH was not proportionally reflected in the yield increment. Higher available phosphorus contents of 7.16 and 6.01 $mg{\cdot}kg^{-1}$ were measured at the liming rates of 4.11 and 5.48 $t{\cdot}ha^{-1}$, respectively. Combined over the two years, 5.45 $t{\cdot}ha^{-1}$ lime application yielded the highest barley total biomass of 19,199 $kg{\cdot}ha^{-1}$ and a grain yield of 4,328 $kg{\cdot}ha^{-1}$, which are 46% and 30% higher than those of the control, respectively. It also yielded the highest marginal rate of return of 477% and a gross margin of 192,857.3 $ETB^{1}{\cdot}ha^{-1}$, which is 53% higher than the control. Based on our results, 5.45 $t{\cdot}ha^{-1}$ of lime appears to have the optimal rate for economically viable barley production in the study area or similar environments.

1. Introduction

Soil acidity is a serious issue in agricultural production, affecting approximately 50% of arable lands worldwide [1, 2]. Soil acidity can reduce cereal grain yield by as much as 50%, and in extreme cases, yields can be reduced to zero [3–5]. Soil acidification is a very complex process and results from natural factors such as soil and climatic factors [4, 5] and/or anthropogenic factors such as the use of inorganic fertilizers [5]. Tropical and subtropical regions are among the most acid-affected areas owing to their high rainfall and associated leaching of base cations [5, 6]. Soil acidity affects plant growth and yield by causing nutrient deficiencies such as P, N, Ca, K, Mg, and Mo and/or inducing aluminum and manganese toxicity [5, 7].

Soil acidity is one of the major crop production constraints in Ethiopia [3], covering 43% of cultivated land [8], of which 28% is strongly acidic [9]. The southern highlands of Ethiopia, where the current study took place, are among the most acid-affected areas of the country. The severity of soil acidity in the area has forced farmers to shift crops, abandoning crops like barley in favor of pasture and a few acid-tolerant crops such as potatoes and onions. It is, therefore, important to develop affordable acid soil management strategies to minimize its impact on crop production.

Amending acid soil with lime is an effective remedy, and its use is growing in Ethiopia [5]. According to this review [5], liming can increase grain yield by 34–252% for wheat, barley, or teff crops in Sub-Saharan Africa (SSA). In the current study area, smallholder farmers are recommended to apply lime and have begun using it. However, the rate of application and the effect that liming will have on their soil, crop productivity, grain yield, and farm income (profitability) are not thoroughly investigated. Although several studies exist on the effects and rate of liming, its effectiveness is also shown to vary depending on the buffering capacity of the soil, soil management, methods of lime application, weather conditions, and agronomic practices such as crop types involved [5]. Therefore, site and/or crop-specific lime application studies are required to identify optimum liming applications that effectively mitigate soil acidity and enhance crop productivity and farm income [10, 11]. The objectives of this study were, therefore, to investigate the effects of different rates of lime application on soil properties, barley yield, and its economic benefit to smallholder farmers.

2. Materials and Methods

2.1. Description of the Study Area. The study was conducted in Bule District of Gedeo Zone, southern Ethiopia (Figure 1). The area lies between 6°04′16″ and 6°23′50″N latitude and from 38°16′20″ to 38°26′11″E longitude (Figure 1(a)). The altitude ranges from 2500 to 3200 m above sea level falling in a tepid moist to cool highlands agroecological zone.

According to traditional agroecology classification, Gedeo Zone comprises Dega (highland), Woina Dega (midland), and Kola (lowland) accounting for 26%, 65%, and 9%, respectively [12]. The altitude of the district ranges from 1500 to 3000 m.a.s.l. The rainfall is bimodal, with the short rain from March to May and the main rain from August to October. The annual rainfall ranges from 1401 to 1800 mm, and the average minimum and maximum temperatures range between 12 and 20°C, respectively [12].

The study area is part of the eastern escarpment of the southern Rift Valley System of Ethiopia. The geology of the area is complex and characterized by tertiary and quaternary period rhyolite and basalt volcanic materials. The surrounding landforms are characterized by diverse topographic features such as plain to steep slopes, undulating to rolling plateaus, scattered moderate hills, dissected side slopes, and river gorges [13], which resulted in the formation of various soil types. Dystric Nitisols and Eutric Cambisols predominate in the area (Figure 1(b)).

The total area of the district is 25,680 ha, with the population of 125,430, of which 117,398 live in rural areas and 8,032 in town [13]. Land use comprises 11,876 ha (46%) perennial crops, 10,115 ha (39%) annual crops, 1,855 ha (7%) forest, 459 ha (1.8%) grazing land, and the remaining is a residential area [13]. Mixed subsistence agriculture is the main source of livelihood. Major annual crops grown are wheat, barley, faba bean, field pea, linseed, vegetables, potato, and onion. Perennial crops such as enset, coffee, and apple are common and often intercropped with trees in the form of traditional agroforestry. Indigenous tree species like *Erythrina abyssinica*, *Arundinaria alpina* (highland bamboo), *Juniperus procera*, and *Hagenia abyssinica*, and an exotic tree species, *Eucalyptus globulus*, are predominant in the landscape.

2.2. Experimental Materials. The soil of the experimental site is Nitisols. Some physical and chemical properties of the soils of the study area are provided in Table 1. The study site was selected based on three criteria: (i) soil pH lower than 5.5, (ii) soil with no previous liming history, and (iii) agroecologically representative for barley production. Barely was the test crop used in the experiment. A high-yielding food variety (HB 1307), commonly grown in the area, was used. Urea (46% N) and NPS (19% N, 38% P_2O_5, and 7% S) fertilizers were applied on the experimental plots at the common rates farmers apply. Agricultural lime ($CaCo_3$), used in the area for treating soil acidity, was applied at various rates described in Section 2.3 to investigate its effects.

2.3. Treatment and Experimental Design. The experiment considered six levels of lime. The initial rate of lime applied was calculated based on the exchangeable acidity (Al^{+3} and H^+), soil bulk density ($g{\cdot}cm^{-3}$), and mass of soil in the upper 0–15 cm soil depth using the following formula [14]:

$$\text{LR, CaCo}_3\left(\frac{\text{kg}}{\text{ha}}\right) = \frac{\text{cmol EA/kg soil} \times 0.15\,m \times 10^4 m^2 \times B.D\left(\text{mg}/m^3\right) \times 1000}{2000}, \tag{1}$$

where LR is the lime requirement (kg/ha), $CaCO_3$ is calcium carbonate, EA is exchangeable acidity, and B.D is the bulk density of soil.

The other lime rates used in the experiment were calculated as 0, 1.5, 2, 2.5, and 3 times the calculated lime requirement (LR) of the soil. The six liming rates involved were 0 (no lime), 2.74, 4.11, 5.48, 6.85, and 8.22 $t{\cdot}ha^{-1}$. The lime was broadcast uniformly by hand across the plots and incorporated into the soil a month before planting (Figure 2). The experiment was laid out in a randomized complete block design (RCBD) with three replications. Blocking was used to control local variability in soil conditions.

The size of each plot was 4 m width × 3 m long (12 m^2) and consisted of 10 planting rows per plot. The spacing between rows, plots, and blocks was 0.3 m, 0.5 m, and

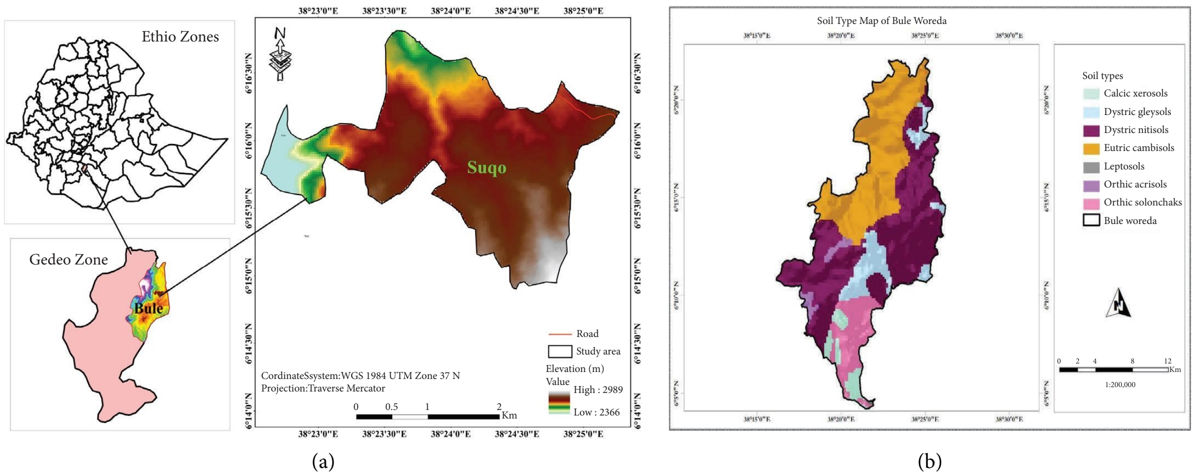

Figure 1: Location map (a) and soil map (b) of the study district.

Table 1: Some soil physical and chemical properties at 0–20 cm depth before treatment application.

Soil texture			Bulk density	Soil chemical properties								
Clay (%)	Silt (%)	Sand (%)	(g/cm^3)	pH	OC (%)	TN (%)	C/N	Av. P (mg/kg)	Ca cmol (+)/kg	Mg	EA	CEC
50.3	34.6	15.1	1.05	5.2	3.5	0.4	8.75	4.24	4.23	0.87	3.48	31.15

Note. EA = exchangeable acidity; CEC = cation exchange capacity; OC = organic carbon; TN = total nitrogen; C/N = carbon to nitrogen ratio; Av. P = available phosphorus; Ca^{+2} = exchangeable calcium; Mg^{+2} = exchangeable magnesium.

Figure 2: Pictures showing application of lime, fertilizer, and other agronomic practices.

1.0 m, respectively. The barely seeds were drilled at the recommended spacing for the crop, which was 20 cm between seeds in a row, and planted at the seeding rate of 90 kg·ha^{-1}. Plantings were carried out on the 15th and 14th of August 2020 and 2021, respectively. Urea and NPS fertilizers were applied at the recommended rate of 73.5 kg N ha^{-1} and 25 kg P ha^{-1}, respectively. To minimize loss and increase N fertilizer use efficiency, it was applied in two splits, i.e., 50% at sowing and the remaining 50% side dressed 30 days after planting. The NPS fertilizer was applied once as basal application during the planting time.

Lime was applied in the first year (2020) of the experiment only. The second year was used to test the residual effects of its application. Seedbed preparation and weeding were performed manually following farmers' regular practices on their fields.

2.4. Soil Sampling and Analysis. Composite soil samples were collected from 0 to 20 cm depth from the experimental plots before applying the treatments and after crop harvest, both in 2020 and 2021. The soil samples were analyzed for several physical and chemical properties following standard soil lab analytical procedures in the Soil and Water Analysis Laboratory of Horticoop Ethiopia PLC. Soil samples were air-dried and ground to pass through a 2 mm sieve, except for the analysis of soil organic carbon and total nitrogen that were ground to pass through a 0.5 mm sieve. The soil physicochemical properties analyzed were soil texture, bulk density, soil pH, available phosphorus, exchangeable bases (Ca^{+2}, Mg^{+2}, K^{+}, and Na^{+}), cation exchange capacity (CEC), exchangeable acidity, exchangeable Al^{+3}, H^{+}, organic carbon, and total nitrogen.

Soil pH (H_2O) was measured with a pH meter in a soil to water ratio of 1 : 2.5. Organic carbon was measured by the wet oxidation method [15]. Total nitrogen was measured using the Kjeldahl method [16], and available phosphorus was determined using the Bray II method. Exchangeable cations (Ca, Mg, K, and Na) were analyzed using the ammonium acetate method. Cation exchange capacity (CEC) was determined by the ammonium acetate method at pH 7. Exchangeable acidity (exchangeable H^{+} and Al^{+3}) was determined by extraction with 1 N KCl followed by titration using the Mehlich-3 method. Soil particle size distribution was determined using the hydrometer method. Soil bulk density was determined through the volumetric method after the soil was oven-dried at 105°C for 24 hours.

2.5. Agronomic, Market, and Farm Input Data Collection. Agronomic data collected were plant height, the number of tillers per plant, spike length, total biomass, grain and straw yields, thousand-grain weight (TGW), and harvest index (HI). Plant height (cm) was measured from the base of the plant to its tip with a measuring tape at full maturity. Five plants were randomly selected per plot, and the average of their heights was analyzed. Spike length (cm) was measured from the bottom of the spike to its tip taking five randomly selected plants per plot at physiological maturity and averaged for per plot value. The number of tillers per plant was determined by counting from 5 randomly selected plants per plot at physiological maturity and averaged for per plot value. Thousand-kernel weight was calculated based on 1000 kernel weight taken from the harvested grain per plot by manually counting and weighing with a sensitive beam balance. Total dry biomass was weighed after air-drying all the harvested above-ground parts of the plants from each plot. Grain yield was determined after carefully separating the grain from the straw by threshing manually and weighing with a sensitive beam balance. The grain yield was adjusted to 12.5% seed moisture content. Grain yield and biomass were quantified per plot and converted to per ha basis for statistical analysis. Economic data such as lime cost and crop and straw prices were collected from local markets.

Quantity and market data for all inputs and outputs were gathered from the local area. Farm gate prices were collected for inputs during planting/sowing seasons, and for outputs, prices at the time of crop harvest were collected. All costs and benefits were in Ethiopian birr (a local currency) and expressed per hectare basis (birr per ha). Accordingly, the average price of 30 birr kg^{-1} for barley grain and 4.11 birr kg^{-1} for barley straw were used to convert the adjusted yields to gross benefits. The market prices of 4.5 birr kg^{-1} for lime and 50 birr per person-day for labor cost were used for variable cost estimation.

2.6. Agronomic and Soil Data Analysis. The collected data were subjected to the analysis of variance (ANOVA) using SAS statistical package version 9.0. Each of the agronomic and soil data was subjected to ANOVA separately for both years and after combining the data from the 2 years. When the effects were found significant at a 5% or lower probability levels, mean separation was conducted with the least significant difference (LSD) using Tukey HSD all-pairwise comparisons. Pearson correlation coefficients (r) were performed among agronomic and soil traits using the mean values. To assess the effects of treatments on barley growth and yield, six single degrees of freedom of orthogonal contrasts were also performed using the procedure of SAS. The total variability for each trait was quantified using a pooled analysis of variance over years using the following model:

$$P_{ijk} = \mu + Y_i + R_{j(i)} + T_k + \mathrm{TY}_{(ik)} + e_{ijk}, \tag{2}$$

where P_{ijk} is the total observation, μ is the grand mean, Y_i is the effect of the i^{th} year, $R_{j(i)}$ is the effect of the j^{th} replication within the i^{th} year, T_k is the effect of the k^{th} treatment, $\mathrm{TY}_{(ik)}$ is the interaction of the k^{th} treatment with the i^{th} year, and e_{ijk} is the random error.

2.7. Partial Budget Analysis. A financial return analysis was performed to investigate the economic feasibility of liming for barley production. The output data (grain yield and straw yield) and input data (market price for labor, lime, etc.) were collected for two consecutive seasons (2020 and 2021) and averaged for analysis. The average grain and straw yields of barley were adjusted downwards by 10% to reflect the difference between the experimental plot yield and the yield farmers would expect from the same treatment under their own management. For a lime treatment to be considered worthwhile for smallholder farmers, the marginal rate of return (MRR) should at least be between 50% and 100% [17]. However, researchers in other parts of the country suggested an MRR of 100% as a realistic value for risk-avert smallholder farmers. Hence, for this study, an MRR of 100% was

Table 2: Mean values of selected soil chemical properties (pH, available P, OC, TN, EA, Ex H^+, and Ex Al^{3+}) as affected by different rates of lime application on Nitisols in southern Ethiopia.

Lime rate ($t{\cdot}ha^{-1}$)	pH		Available P (mg/kg)		OC (%)		TN (%)		Ca^{2+}	EA (cmol/kg)		H^+ (cmol/kg)		Al^{3+} (cmol/kg)	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2020	2021	2020	2021	2020	2021
Control (0)	5.04d	4.97c	5.63a	4.68a	5ab	4.22a	0.48ab	0.49a	4.8 d	2.59a	4.15a	0.47a	1.79a	2.13a	2.36a
2.74	5.29cd	5.18c	6.94b	3.83a	5.07ab	4.29a	0.48ab	0.49a	8.15cd	0.88b	1.94b	0.26b	1.39ab	0.61b	0.55b
4.11	5.66bc	5.67b	6.95b	5.08a	5.12a	4.24a	0.49ab	0.5a	10.43bcd	0.33b	1.04bc	0.14c	0.80bc	0.19b	0.72ab
5.54	5.64bc	5.70b	7.05b	4.19a	5.01ab	4.17a	0.51a	0.65a	11.52bc	0.36b	0.49c	0.16c	0.49cd	0.20b	ND
6.85	6.11ab	5.83b	7.95ab	3.78a	4.95ab	4.15a	0.48ab	0.48a	14.34ab	0.71b	0.59bc	0.22bc	0.59cd	0.49b	ND
8.22	6.54a	6.37a	7.92ab	4.9a	4.8b	3.86b	0.46b	0.46a	17.91a	0.45b	0.16c	0.14c	0.16d	0.31b	ND
Significance level	**	***	NS	NS	NS	**	NS	NS	*	***	***	***	***	***	*
LSD (0.05)	0.55	0.44	1.89	1.34	0.3	0.24	0.04	0.22	6.18	0.66	1.41	0.10	0.61	0.57	
CV (%)	5.34	4.48	13.41	18.6	3.33	3.27	4.69	25.19	30.33	41.09	38.14	23.89	30.42	38.12	27.96

Note. Significant at $^{*}p \le 0.05$, $^{**}p \le 0.01$, and $^{***}p \le 0.001$. Within a column, means followed by different letters are significantly different at $p < 0.05$. LSD: least significant difference; CV: coefficient of variation; NS: not significant; ND: not detected.

taken as a benchmark. The 6.85 and 8.22 $t{\cdot}ha^{-1}$ treatments were excluded from the marginal analysis. For each pair of the remaining treatments, a percentage marginal rate of return (% MRR) was calculated. MRR was calculated using the following formula:

$$\mathrm{MRR}\,(\%) = \frac{\text{Change NB}}{\text{Change TVC}} * 100, \tag{3}$$

where TVC = total variable cost, NB = net benefit, and MRR = marginal rate of return.

3. Results and Discussion

3.1. Effect of Liming on Soil Properties. Liming significantly affected soil pH, including its residual effect. All lime-treated soils had higher mean pH values in 2020 and 2021 than the control plot (Table 2). Soil pH increased progressively with increased quantity of lime applied. The highest pH values of 6.54 and 6.37 in 2020 and 2021, respectively, were obtained from soils of the plots that received the largest quantity of lime (8.22 $t{\cdot}ha^{-1}$), whereas the lowest values (5.04 and 4.97, respectively) were measured in the soils of the control plots (Table 2).

The combined data from the 2 years also showed a significant ($p < 0.001$) effect of liming on soil pH (Table 3). A significantly high pH value of 6.46 was recorded from soils of the plots that received the largest quantity of lime (8.22 $t{\cdot}ha^{-1}$), while the lowest pH value of 5.01 was measured from the soils of the control plots. Soil pH increased by 0.46, 0.47, 0.77, and 1.25 units with the applications of 2.74, 4.11, 5.48, 6.85, and 8.22 $t{\cdot}ha^{-1}$ lime, respectively. Though the effects of year on soil pH are not significant, a relatively higher pH of 5.71 was obtained in 2020, while a pH of 5.62 was obtained in 2021 (Table 3).

These results concur with studies that indicated positive effects of liming on soil pH including strong residual effects, which could last for five to seven years depending on texture, buffering capacity of the soils, and the quality of lime applied [5, 10, 18]. For instance, Buni [10] found an increase in soil pH, ranging from 0.48 to 1.1 units following the application of lime rates from 0.55 to 2.2 $t{\cdot}ha^{-1}$ in Ethiopia. Other studies [18, 19] also reported a marked increase in soil pH in response to liming in southern and western Ethiopia, respectively.

Soil EA and exchangeable H^+ and Al^{3+} were significantly ($p = 0.001$) decreased in response to lime application during the two years of the experiment (Table 2). The lowest EA of 0.16 cmol/kg was obtained from the plot treated with the highest rate of lime (8.22 $t{\cdot}ha^{-1}$) followed by 0.49 cmol/kg in plots treated with 5.54 $t{\cdot}ha^{-1}$ lime, while the highest EA values of 2.59 and 4.15 $cmol{\cdot}kg^{-1}$ soil were obtained from control plots in 2020 and 2021, respectively (Table 2). Exchangeable Al^{3+} was not detected in plots treated with lime rates of 5.54, 6.85, and 8.22 $t{\cdot}ha^{-1}$ in 2021 (Table 2).

The increase in soil pH following liming could be attributed to the release of base cations such as Ca^{+2} and Mg^{+2} to displace acidic cations such as Al^{+3} and H^+ from the soil colloids and subsequently precipitate in the form of $Al(OH)_3$ [5]. When lime is added to acid soil that contains high Al^{3+} and H^+ concentrations, the soil solution will become charged with Ca^{2+}. This ion will get in exchange with H^+ and Al^{3+} ions on the exchange complex and consequently increase the soil pH. Similarly, the observed low concentration of acid causing cations (H^+ and Al^{3+}) in plots treated with lime is in line with the findings of [10] who reported decreased Al^{+3} concentrations between 0.88 and 1.19 cmol/kg units following lime treatment in Ethiopia. Other studies (e.g., [11, 18, 19]) on liming of acidic soils reported improved soil chemical properties and crop yield.

The combined data from the two years also showed significantly ($p < 0.001$) lower EA and exchangeable Al^{3+} and H^+ (Table 3). The highest soil EA and exchangeable H^+ and Al^{+3} were recorded from the control plots (Table 3). In contrast, the lowest EA of 0.31 cmol/kg was measured from plots treated with the liming rate of 8.22 $t{\cdot}ha^{-1}$. Similarly, the application of 8.22 $t{\cdot}ha^{-1}$ of lime resulted in lower exchangeable H^+ of 0.15 cmol/kg compared to 1.13 cmol/kg soils in the control plot. Exchangeable acidity was significantly reduced by 2.02, 2.8, 3.06, and 3.17 cmol/kg at lime application rates of 2.74, 4.11, 5.48, 6.85, and 8.22 $t{\cdot}ha^{-1}$, respectively (Table 3). A slightly higher EA of 1.4 cmol

Table 3: Effects of lime application on soil chemical properties combined over 2 years on Nitisols in southern Ethiopia.

Treatment	pH (H_2O)	Av. P (mg kg^{-1})	CEC	Ca^{2+} (Cmol kg^{-1})	K^+ (Cmol kg^{-1})	OC (%)	TN (%)	C : N ratio	EA (Cmol kg^{-1})	H^+ (Cmol kg^{-1})	Al^{+3}
Year											
2020	5.71	7.74a	28.61	9.72a	0.41a	5.01a	0.49	10.38a	0.89a	0.23a	0.65
2021	5.62	4.41b	28.13	11.19b	0.49b	4.16b	0.51	8.36b	1.40a	0.87b	0.53
Significance level	NS	*	NS	*	*	*	NS	*	NS	*	NS
LSD (0.05)	0.37	0.69	3.89	9.6	0.11	0.05	0.12	0.96	0.99	0.55	0.2
Lime rate ($t{\cdot}ha^{-1}$)											
Control (0)	5.01d	5.62ab	27.43	4.80b	0.41ab	4.67a	0.49	9.62	3.37a	1.13a	2.25a
2.74	5.23cd	5.39ab	28.65	8.15b	0.41ab	4.68a	0.49	9.67	1.41b	0.83ab	0.58b
4.11	5.66bc	7.16 a	29.6	10.43ab	0.47a	4.68a	0.5	9.45	0.68bc	0.47bc	0.21c
5.54	5.67bc	6.01ab	28.41	11.52ab	0.45ab	4.59ab	0.58	8.46	0.42bc	0.32c	0.10c
6.85	5.97ab	5.86ab	28.12	14.34ab	0.35ab	4.55ab	0.48	9.63	0.65c	0.41c	0.25c
8.22	6.46a	6.42b	28.02	17.91a	0.39b	4.33b	0.46	9.4	0.31c	0.15c	0.15c
Significance level	***	*	NS	**	**	*	NS	NS	***	***	***
LSD (0.05)	0.49	1.63	3.38	3	4.2	0.267	0.16	1.36	0.77	0.42	0.17
CV (%)	4.81	14.82	6.57	6	10.2	3.21	17.63	21.56	28.21	22.25	28.79

Note. Significant at $^{*}p \le 0.05$, $^{**}p \le 0.01$, and $^{***}p \le 0.001$; NS: not significant. Within a column, means followed by different letters are significantly different at $p < 0.05$. LSD: least significant difference; CV: coefficient of variation.

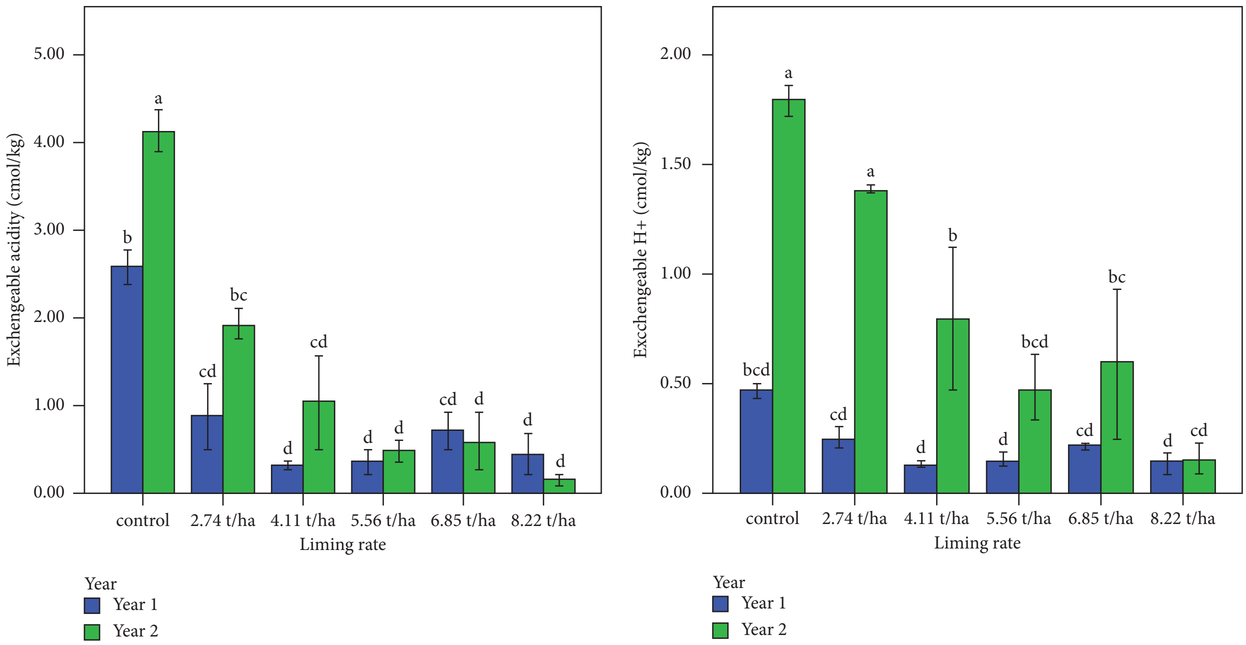

Figure 3: The interaction effects of liming and year on exchangeable acidity and H^+ on Nitisols in southern Ethiopia (different letters in the columns are significantly different at $p < 0.05$).

(+) kg^{-1} soil was measured in 2021 than an EA of 0.84 cmol (+) kg^{-1} in 2020 (Table 3).

A complete absence of Al^{3+} was observed in plots that were treated with higher rates of lime in the second year (Table 2), and this indicates the complete replacement of Al^{3+} ions with Ca^{2+} ions. This is also reflected in the significant effect that liming had on exchangeable Ca^{++}. In the 2020 cropping period, significantly higher exchangeable Ca^{2+} of 17.91 cmol/kg was measured from a plot treated with 8.22 t·ha^{-1} lime, followed by 14.34 cmol·kg^{-1} soil from the application of 6.85 t·ha^{-1}. On the contrary, the lowest exchangeable Ca^{+2} content of 4.79 cmol·kg^{-1} was measured in the soils of the control plots (Table 2). Exchangeable Ca^{+2} increased progressively with the increased rate of lime application. Exchangeable K^+ was not significantly ($p < 0.05$) influenced by lime rates (Table 3). However, in terms of absolute values, lime rates of 4.11 and 5.45 t·ha^{-1} had the highest exchangeable K^+ concentrations of 0.47 and 0.45 cmol·kg^{-1} soil, respectively, compared to the K value of 0.41 cmol·kg·ha^{-1} measured from the control treatment (Table 3).

The interaction effect of lime and year was not significant for most soil and agronomic variables except for EA and H^+ (Figure 3). A significantly higher EA of 4.15 cmol/kg of soil was measured from the control treatment without lime application in the 2021 cropping season, followed by 2.59 cmol/kg soil from the control treatment in the 2020 cropping season, while the lowest EA of 0.16 cmol/kg was measured from the application of 8.22 t/ha lime in the 2021 cropping season, followed by 0.33 cmol/kg from the application of 4.11 t/ha lime in the 2020 cropping season (Figure 3). Liming and year also had a significant ($p = 0.001$, Figure 3) interaction effect on exchangeable H^+. A significantly higher exchangeable H^+ of 1.79 cmol/kg was measured from the control treatment in the 2021 cropping season, followed by 2.74 t/ha lime year 2 and control, while the lowest amount of exchangeable H^+ of 0.14 cmol/kg was measured from the interaction of year 1 and 4.11 t/ha lime and year l and 8.22 t/ha lime (Figure 3). The observed low concentrations of H^+ in the plot treated with lime indicate the dislocation of Ca carbonate into Ca^{2+} and Co_3^{-}, thereby resulting in the replacement of H^+ ions by CO_3^{-} ions.

Despite the effects on several soil properties, the application of lime did not significantly increase plant nutrient availability (e.g., available P and N) in both the 2020 and 2021 cropping seasons (Table 2). However, in terms of absolute values, higher available P was measured in all plots treated with lime compared to the control in the first year of the experiment (Table 2). Furthermore, applications of lime at the rates of 4.11 and 5.45 t·ha^{-1} increased available P from 4.24 mg/kg before treatment to 7.16 in 2020 and 6 mg/kg in 2021. These are the largest change in available P among all treatments applied (Tables 1 and 3). The effect of lime application on available P combined over the 2 years was also not significant ($p > 0.05$) (Table 3).

Liming increases P availability by deactivating the active Al^{3+} ions that hinder P availability. The application of lime increased P by enhancing the release of P fixed by Al/Fe and converting plant unavailable P into available P [20–23]. Asrat et al. [19] reported a significant improvement in available P from 5.36 to 7.04 mg·kg^{-1} due to the application of 3.75 t·ha^{-1} lime. A similar study by the authors of [9] also reported P release in the range of 15.1–17.3 mg·kg^{-1} compared to available P measured from untreated soil (4.2–7.1 mg·P·kg^{-1}) with an initial pH value of 4.0. Year of cultivation had a significant ($p = 0.05$) effect on available P. Overall, improvement in soil nutrient availability due to

Table 4: Yield and yield components of barley as affected by different levels of lime on Nitisols in southern Ethiopia.

Lime rate ($t\ ha^{-1}$)	pH (cm)		NT		SL (cm)		GY (kg/ha)		AGB (kg/ha)		SY (kg/ha)		HI		TGW (g)	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
Control (0)	92.73b	76.25b	6	1.2	6.35	7.14c	3179b	3472.3b	12010b	14236a	8831b	10763.7	26.67a	24.67ab	41.47a	59
2.74	96.4ab	79.2ab	7.17	1.27	6.57	7.69abc	3308b	3819.7ab	13263.3ab	17361.3a	9955ab	13541.7	25abc	22.67b	39.5a	67.67
4.11	104.7ab	85.39ab	5.77	1.4	6.33	7.82abc	3434.3ab	4687.7a	13743.3ab	16027.7a	10309ab	11340.7	25.3abc	31a	41.53a	66.67
5.54	105.10ab	88.81a	6.52	1.67	6.8	7.98ab	3794.3a	4861.3a	16523.3ab	21874.7a	12729a	17014	23bc	22b	38.4	64.67
6.85	99.57ab	80.39ab	9.31	1.53	6.8	7.38bc	3529.3ab	3993.3ab	13626.7ab	18402.7a	10097.3ab	14410	26ab	22b	37.37	71.3
8.22	108.63a	88.97a	7.33	1.6	7.87	8.18a	3610.7ab	3993.3ab	16176.7a	17013.3a	12566a	13020	22.33c	23.67ab	38.13	65.67
Significance level	*	*	NS	NS	NS	*	*	*	*	*	*	NS	*	*	NS	NS
LSD (0.05)	14.25	11.38	4.44	0.59	1.92	0.75	442.31	1169.7	3319.6	8180.4	2943.3	14.6	3.34	7.97	7.3	14.78
CV (%)	7.74	7.52	34.79	22.56	15.57	5.36	6.99	15.59	12.83	25.71	15.05	7207.3	7.77	17.99	10.21	12.4

Note. pH = plant height, NT = number of tillers, SL = spike length, GY = grain yield, AGB = above-ground biomass (kg/ha), SY = straw yield (kg/ha), HI = harvest index, and TGW = thousand-grain weight (gm).

Table 5: Yield and yield components of barley as affected by lime and year combined over 2 years on Nitisols in southern Ethiopia.

Treatments	Plant height (cm)	Tillers per plant (no.)	Spike length (cm)	Total biomass (kg/ha)	Grain yield (kg/ha)	Straw yield (kg/ha)	HI (%)	TGW (g)
Year								
2020	101.19	7.0a	6.8b	14224b	3476b	10748b	24.4	39.4b
2021	83.17	1.4b	7.7a	17486a	4138a	13348a	23.7	45.8a
Significance level	**	*	*	*	*	*	NS	**
LSD (0.05)	6.5	0.47	0.52	3236	558	2494	1.3	10.7
Lime rate ($t{\cdot}ha^{-1}$)								
Control	84.5b	3.6b	6.7	13123c	3326b	9797c	25.3ab	50.2
2.74	87.8ab	4.2ab	7.1	15312ab	3564ab	11749ab	23.3ab	53.6
4.11	95ab	3.6b	7.1	14886b	4061ab	10825b	27.3a	54.1
5.54	97ab	4.1ab	7.4	19199a	4328a	14872a	22.5c	51.5
6.85	90ab	5.4a	7.1	16015ab	3761ab	12254ab	23.5ab	54.3
8.22	98.8a	4.5ab	8.0	16595ab	3802ab	12793ab	22.9b	51.9
Significance level	**	*	NS	*	*	*	*	NS
LSD (0.05)	12.8	1.4	1.4	4227	881	3492	5.1	10.6
CV (%)	7.6	21.1	11.1	19.6	12.7	21.1	11.7	12.2

Note. Significant at $^{*}p \leq 0.05$, $^{**}p \leq 0.01$, and $^{***}p \leq 0.001$; NS: not significant. Within a column, means followed by different letters are significantly different at $p < 0.05$. LSD: least significant difference; CV: coefficient of variation.

liming was minimal, which may imply the need for integrated soil management for enhancing nutrient availability [24].

Combined data from the two years showed a significantly higher available P of 7.74 mg/kg in 2020 compared to 4.41 mg/kg in 2021. The observed lower available P in the second year could be associated either with the refixation of P due to the lowering in soil pH or the increase in exchangeable acidity in that year.

Applications of lime did not significantly affect TN in both the 1st and 2nd year of the experiment (Table 2). However, in absolute terms, a higher TN of 0.65% and 0.51% was measured from plots treated with 5.54 t/ha in the 2021 and 2020 cropping seasons, followed by 0.5% and 0.49% in plots treated with 4.11 t/ha in the same year (Table 2). The increased TN in plots treated with lime indicates the potential of lime for enhancing OM decomposition. Soil OC was significantly ($p < 0.01$) affected by lime application in 2021, while the influence of lime on soil OC in the 2020 cropping period was not significant (Table 2). In the 2021 cropping season, a significantly low OC of 3.86% was measured from plots treated with the highest rate of 8.22 t/ha lime (Table 2), implying that higher rates of lime application may not be beneficial for microbial activities and associated OM decomposition.

On the contrary, data combined over the two years showed a significant ($p < 0.05$) effect of lime application on OC (Table 3). The lowest significant OC of 4.33% was obtained from the application of the highest rate of lime (8.22 t/ha). Low soil OC contents in plots treated with the highest rate of lime (8.22 t/ha) compared to the control plots could be associated with rapid changes in pH, which might not be beneficial for microbial activities and OC decomposition.

3.2. Effects of Liming on Barley Yield and Yield Components. The application of lime significantly ($p < 0.05$) affected grain yield, total biomass, and plant height (Table 4). Separate analysis of data from the two years showed that the highest grain yields of 4,861 and 3,794.3 $kg{\cdot}ha^{-1}$ were obtained in 2021 and 2020 from plots treated with 5.45 $t{\cdot}ha^{-1}$, respectively. These are 40% and 19.4% higher than the yields obtained from the control plot, respectively (Table 4). The higher grain and biomass yield in 2021 than 2020 from the application of 5.54 $t{\cdot}ha^{-1}$ of lime may reflect a higher residual effect of liming on crop yield than fresh application. Similarly, a significantly higher biomass of 21,875 and 16,523 $kg{\cdot}ha^{-1}$ was obtained from plots treated with 5.45 $t{\cdot}ha^{-1}$ in the 2021 and 2020 cropping seasons, respectively, which are 53.7% and 37.6% higher than biomass collected from the control plot in the respective years (Table 4).

Significantly higher plant heights of 108.63 and 88.97 cm were measured from plots treated with 8.22, followed by 88.97 and 88.81 cm from plots treated with 5.45 $t{\cdot}ha^{-1}$ lime in 2020 and 2021, respectively (Table 4). These results agree with a recent review [5] that reported a grain yield increment in the range of 34–252% in wheat, barley, and teff in response to liming in SSA. The recent study by (32) also revealed that the application of lime in combination with inorganic fertilizer increased teff yield by 43–54% and wheat yield by 28–32%.

The combined analysis of data from the two years indicates a significant effect of liming on yield and other yield components except for spike length and thousand-grain weight (Table 5). Interyear variations in barley yield and yield components were also significant except for the harvest index (HI) (Table 5). However, the interaction of the lime rate and year was not significant (Figure 3). Applications of different rates of lime had a highly significant ($p < 0.01$) effect on plant height and a significant effect ($p < 0.05$) on the number of tillers per plant, straw yield, HI, grain yield, and total biomass with exception of spike length and thousand-grain weight (Table 5). Across the two years, the application of lime at the rate of 5.45 1 $t{\cdot}ha^{-1}$ resulted in the highest barley grain yields of 4,328 $kg{\cdot}ha^{-1}$ and the total biomass of 19,199 $kg{\cdot}ha^{-1}$ which are 30% and 46% higher than grain and biomass yield collected from the control plot, respectively (Table 5). Conversely, the lowest grain yield of 13123 $kg{\cdot}ha^{-1}$

Table 6: Correlation coefficients among plant parameters and soil nutrient concentrations as affected by different rate of liming on Nitisols in southern Ethiopia.

Parameters	Height	Tillers	Yield	Biomass	pH	Av. P	CEC	OC	TN
Tillers	0.76^{**}								
Yield	0.41^{*}	0.46^{**}							
Biomass	0.57^{**}	0.43^{**}	0.84^{***}						
pH	0.38^{*}	0.12^{ns}	0.36^{*}	0.35^{*}					
Av. P	0.56^{**}	0.77^{**}	0.49^{**}	0.51^{**}	-0.57^{**}				
CEC	0.26^{ns}	0.27^{ns}	0.11^{ns}	0.06^{ns}	0.11^{ns}	0.03^{ns}			
OC	0.64^{**}	0.82^{***}	0.54^{**}	0.49^{**}	0.15^{ns}	0.79^{**}	0.14^{ns}		
TN	0.52^{**}	0.39^{*}	0.49^{**}	0.46^{**}	0.04^{ns}	0.22^{ns}	0.02^{ns}	0.36^{*}	
EA	-0.51^{**}	-0.24^{ns}	-0.39^{*}	-0.32^{*}	-0.67^{**}	-0.01^{ns}	-0.16^{ns}	-0.06^{ns}	-0.09^{ns}

$^{*}p \leq 0.05$, $^{**}p \leq 0.01$, and $^{***}p \leq 0.001$; ns: not significant.

and the total biomass of 3326 kg·ha^{-1} were obtained from the control treatment (Table 5).

Grain yield response to the lime rate in ascending order was 2.74 (7%) < 6.85 (13%) < 8.22 (14%) < 4.11 (22%) < 5.48 (30%) t·ha^{-1} (Table 5). These results indicate that high lime rates such as 6.85 and 8.22 t·ha^{-1}, despite sharply increasing soil pH had their pH effects, were not reflected in a proportional increase in barley yield. The sharp increase in pH might adversely affect microbial activities, OM decomposition, N cycle and nutrient imbalance, and barley growth and yield [20, 24]. For instance, lower soil OC and TN were measured from plots that received the highest lime rate of 8.22 t·ha^{-1} (Tables 2 and 3). The same trend was observed with the application of a low rate of lime, i.e., 2.74 t·ha^{-1}, indicating that both low and high rates could affect barely yield negatively. Other yield components data such as straw yield and HI were also significantly affected in response to lime application (Table 5). A significantly higher HI of 27.3% was measured from plots treated with 4.11 t·ha^{-1}. Likewise, a higher HI of 31% was measured from the same treatment in the 2021 cropping period (Table 4). The observed relatively higher HI in plots treated with 4.11 t·ha^{-1} lime could be associated with improvement in plant available P compared to other plots (Table 3).

Improvements in yields of barley in plots treated with 4.11 and 5.45 t·ha^{-1} lime could be associated with increasing pH and an increase in available plant nutrients (e.g., available P) and exchangeable cations (Ca^{+2} and K^{+}) (Tables 2 and 3). Another reason for the improvement in barley yield in plots treated with 4.11 and 5.45 t·ha^{-1} lime might be the reduction of EA and H^{+} and Al^{+3} (Tables 2 and 3) which is in line with the finding of the authors of [25–27]. It is obvious that the neutralization of aluminum and manganese could create a conducive environment for the growth of plant roots, and this may have led to greater uptake of water and nutrients [12, 28, 29]. This is confirmed by the observed positive and strong correlations between barley yield and desirable soil properties (pH), available P, OC, and TN ($r = 0.36$, 0.49, 0.64, 0.52), respectively (Table 6). Even though liming improved barley yield, barley yield gain measured in this study was lower than reported by other studies [5, 11, 18]. For instance, Desalegn et al. [11] reported barley yield increments of 133% resulting due to integrated use of lime and inorganic fertilizers.

The combined analysis of variance over 2 years showed that the year effect was significant ($p \leq 0.05$) for the number of tillers per plant, spike length (cm), total biomass (kg·ha^{-1}), grain yield (kg·ha^{-1}), and straw yield (kg·ha^{-1}) and ($p \leq 0.01$) for plant height (cm) and thousand-grain weight (g), but not for the harvest index (HI) of food barley (Table 5). The highest mean barley grain yield (4138 kg·ha^{-1}) and total biomass (17486 kg·ha^{-1}) were obtained in the 2020 cropping season (Table 5). This result is in line with the finding of the authors of [5, 30] who found a higher barley yield in the third year than the yields obtained in the first and second years after the application of lime in Ethiopia. The residual effects of liming are known to last five to seven years [5, 24]. Likewise, a significantly higher thousand-grain weight of 45.8 g was recorded in 2021 than 39.4 g recorded in 2020 (Table 5). The improvement in barley biological yield in the second year could be associated with high rainfall distribution and the decline in Al^{3+} due to the residual effects of liming (Tables 2 and 3).

Generally, the application of lime improved soil properties and nutrient availability and reduced Al^{+3}, Mn^{+2}, and H^{+} toxicity (Tables 2 and 3). The combined yield and biomass over the 2 years showed that the most optimal rates of lime for barley production in the study area were 4.11 and 5.54 t·ha^{-1}, with respective yield gains of 27 and 30%, respectively. The observed yield gain ranged between 7 and 30% was lower than the yield gain of 52–81% reported by the authors of [11] but within a similar yield gain of 15–68% reported by the authors of [31] and higher than the yield gain of 4–41% reported by the authors of [30] in the highlands of Ethiopia. The observed lower relative grain yield response to lime application in this study could be due to sole application of lime, and thus, the recommended lime rate should be integrated with inorganic or organic fertilizer for increasing barley yield.

Partitioning of the treatments into single degrees of freedom of orthogonal contrasts revealed that grain yield, total biomass, and plant height of barley significantly differed due to different rates of lime (Table 7). The first contrast (control vs. lime treatment (T)) had a highly significant ($p < 0.05$) effect on grain yield, total biomass, and plant height of barley. The results showed no significant effects between T2 vs. T3–T6 and T3 vs. T4–T6 on grain yield (Table 7). This clearly indicates that there are no significant

Table 7: Variance ratios and probabilities of single degrees of freedom of orthogonal contrasts for the effects of different rates of liming on crop growth and yield on Nitisols in southern Ethiopia.

Parameters	Control vs. (T2–T6)	T2 vs. T3–T6	T3 vs. T4–T6	T4 vs. T5-T6
Plant height				
Variance ratio	425.6	262.5	0.18	26.3
F-probability	0.0067	0.0282	0.9510	0.4644
Number of tillers				
Variance ratio	2.86	0.15	5.23	2.88
F-probability	0.3200	0.8198	0.1831	0.3183
Spike length				
Variance ratio	1.79	0.34	0.80	0.11
F-probability	0.0976	0.4618	0.2601	0.6704
Grain yield				
Variance ratio	$1.67E+06$	863773	42583	$1.19E+06$
F-probability	0.0151	0.0710	0.6776	0.0363
Total biomass				
Variance ratio	$5.37E+07$	$8.89E+06$	$2.56E+07$	$3.35E+07$
F-probability	0.0391	0.3818	0.1444	0.0972
Straw yield				
Variance ratio	$3.65E+07$	$4.22E+06$	$2.77E+07$	$2.21E+07$
F-probability	0.0514	0.4911	0.0864	0.1235
Harvest index				
Variance ratio	9.34	1.63	112.50	4.00
F-probability	0.3551	0.6966	0.0034	0.5428
1000 grain weight				
Variance ratio	40.898	1.80	10.20	10.13
F-probability	0.3371	0.8387	0.6289	0.6300

Table 8: Marginal and partial budget analyses of different rates of lime application combined over 2 years on Nitisols in southern Ethiopia.

	Lime rate ($t \cdot ha^{-1}$)					
	Control	2.74	4.11	5.54	6.85	8.22
Average grain yield ($kg \cdot ha^{-1}$)	3330	3560	4060	4330	3760	3800
Adjusted grain yield ($kg \cdot ha^{-1}$)	2990	3210	3650	3890	3390	3420
Average straw yield ($kg \cdot ha^{-1}$)	9800	21700	21130	27600	22350	25360
Adjusted straw yield ($kg \cdot ha^{-1}$)	8820	19530	190200	24840	20120	22820
Gross benefit from grain	89,791.5	96,219.9	109,644.3	116,847	101,552.1	102,650.2
Gross benefit from straw	36,240.8	80,282.4	78,173.2	102,094	82,676.0	93,803.3
Total gross benefit (ha^{-1})	126,032.2	176,502.3	187,817.5	218,942.1	184,228.1	196,453.5
Field cost of lime (ha^{-1})	—	11,234.0	16,851.0	22,468.0	28,085.0	33,702.0
Field cost of labor (ha)	—	1,808.4	2,712.6	3,616.8	4,521.0	5,425.2
Total variable cost (birr/ha)	—	13,042.4	19,563.6	26,084.8	32,606.0	39,127.2
Net benefit (birr/ha)	126,032.2	163,459.9	168,253.9	192,857.3	151,622.1	157,326.3
MRR		1.74	3.87	4.77	D*	D*
MRR (%)		174%	387%	477%		

*Dominated; *1USD = 47 Ethiopian birr at the time of the study. Price of barley grain = 30 birr kg^{-1}; price of barley straw = 4.11 birr kg^{-1}. The market price of lime = 4.5 birr kg^{-1}; labor cost for spreading lime = 50 ETB per person-day.

differences among the four treatments, i.e., between T2, T3, T5, and T6 on barley grain yield as evidenced in the yield data in Table 4. A study by the authors of [5] also reported similar results on yields of barley, wheat, and teff due to the application of integrated soil fertility management practices.

3.3. Correlations among Soil Properties, Barley Yield, and Yield Components. Pearson correlation analysis indicated that plant height was positively correlated with soil pH ($r = 0.38^{*}$), soil available P ($r = 0.58^{**}$), soil OC ($r = 0.64^{**}$), and total N ($r = 0.52^{**}$). Similarly, grain yield and total biomass had positive and strong correlations with soil pH ($r = 0.36^{*}$ and 0.35^{*}), soil available P ($r = 0.49^{**}$ and 0.51^{**}), soil OC ($r = 0.54^{**}$ and 0.49^{**}), and TN ($r = 0.49^{**}$ and 0.46^{**}). Conversely, EA was negatively correlated with plant height ($r = -0.51^{**}$), grain yield ($r = -0.39^{*}$), and total biomass ($r = -0.32^{*}$), indicating an inverse relationship where yield and growth parameters increased as EA decreased (Table 6). Grain yield was positively and strongly correlated ($r = 0.84^{***}$) with total biomass (Table 6). The grain yield was also positively correlated with the number of tillers per plant and plant height ($r = 0.46^{**}$ and 0.41^{*}), respectively (Table 6). Total biomass had a positive and strong correlation with plant height and the number of tillers per plant ($r = 0.57^{**}$ and 0.43^{**}, respectively). A systematic review by Agegnehu et al. [5] reported related patterns of correlations between the barley grain yield and soil pH level and wheat grain yield and soil pH [32], implying the sensitivity of barley to soil acidity.

3.4. Economic Viability of Liming. The application of $5.54\,t{\cdot}ha^{-1}$ lime provided the highest net benefit of ETB $192{,}857.3\,ha^{-1}$ (Table 8). The net benefit from the control treatment was ETB $126{,}032.2\,ha^{-1}$ (Table 6). It is apparent that changing lime rates from $4.11\,t{\cdot}ha^{-1}$ to $5.48\,t{\cdot}ha^{-1}$ gave a positive and highest MRR of 477%. As a rule of thumb, an MRR of below 100% is considered low and unacceptable to offset management and transaction costs [17]. The economic return from using $5.48\,t{\cdot}ha^{-1}$ of lime was fourfold greater than the minimum marginal rate of return required to justify the acceptance of lime application, implying a return of 4.77 birr on every birr spent in liming application. This could be attractive enough to motivate farmers to adopt liming.

4. Conclusions

The results from this study showed significant improvements in soil chemical properties, nutrient availability, and crop yield and better economic return from liming of acidic soils. Considering the amendment effect of soil acidity, crop yield, and economic benefits, we recommend $5.45\,t{\cdot}ha^{-1}$ of lime as the optimum rate for barley production on acidic Nitisols in southern highlands of Ethiopia followed by the second best rate of $4.11\,t{\cdot}ha^{-1}$. Applications of 4.11 and $5.54\,t{\cdot}ha^{-1}$ of lime increased grain yield by 22 and 30% over the control, respectively. The slight rise in EA and a corresponding decline in soil pH in the second year compared to the first year may be an indication of a weaker residual effect of liming. A longer term study than considered in this study may provide a better picture of the residual effects of liming in the area. In economic terms, return from acid soil amendment with liming far outweighs investment. For example, the application of $5.48\,t{\cdot}ha^{-1}$ of lime provided an MRR of 477%, implying a return of 4.77 birr on every birr spent in liming application. Further experiments on integrated acid soil amendments involving different rates of lime and organic and inorganic fertilizers are suggested to see improvements in the overall physicochemical and biological properties of soils and crop yield.

Data Availability

Data will be made available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Getahun Haile designed the field experiment, collected soil and agronomic data, analyzed the data, and wrote the manuscripts. Habtamu Berihun and Helina Abera contributed to field data collection. Getachew Agegnehu contributed to analyzing the agronomic and soil data and reviewing the manuscript and quality assuring the overall work. Mulugeta Lemenih contributed to reviewing the manuscript and quality assuring the overall work.

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