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Research article

Effect of lime rates and method of application on soil properties of acidic Luvisols and wheat (*Triticum aestivum*, L.) yields in northwest Ethiopia

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ABSTRACT

Soil acidity has become a major constraint that threatens sustainable agricultural production in Ethiopia. This study was conducted to evaluate effects of lime rates and application methods on selected soil properties and wheat (*Triticum aestivum*, L.) yields on acidic Luvisols of northwestern Ethiopia. The treatments included control, 0.5, 1, 2 and 3 t ha^{-1} lime drilled along the seed rows and 2, 3, 6 and 12 t ha^{-1} lime applied in broadcasting method. The experiment was arranged in a randomized complete block design (RCBD) with three replications. Lime rates applied for this experiment were quantified using exchangeable acidity and Buffer pH methods. To analyze selected soil properties, composite soil samples were collected immediately before sowing and after harvest. Results revealed that liming significantly increased soil pH, available phosphorus, and exchangeable bases but markedly reduced exchangeable Al^{3+} contents. The lime rates determined by buffer pH method were greater in ameliorating soil acidity, increasing soil nutrients status and crop yields than exchangeable acidity. Besides, lime application along the row was better in overcoming soil acidity constraints and increasing crop yields compared to broadcast application. Application of 12 t ha^{-1} lime in the broadcasting method, 3 t ha^{-1} and 2 t ha^{-1} lime drilling along the row increased wheat grain yield by 65.10, 49.80 and 27.05%, respectively, compared to the control. Likewise, partial budget analysis showed that the highest net benefit (51,537 Birr ha^{-1}) was obtained from plots amended with 3 t ha^{-1} lime while the lowest economic profit (31,627.5 Birr ha^{-1}) was recorded from treatments that received 12 t ha^{-1} lime. Thus, we concluded that application of 3 t ha^{-1} lime in row is a promising practice to mitigate soil acidity and increase available nutrients, exchangeable bases and crop yields in the study area and similar soil types elsewhere.

1. Introduction

Soil acidity is among the major soil fertility bottlenecks causing low crop productivity worldwide [1–3]. Acidic soils consist of nearly 40–50% of the world's total potential arable land [4]. Besides, about 43% of agricultural land in the Ethiopian highlands is affected by soil acidity [5]. The west, northwest, southwest and south regions of the country that receive high amounts of rainfall and

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have good potential for agriculture are mainly affected by soil acidity [6].

High concentrations of Al, Mn and Fe, and extreme deficiency of essential plant nutrients such as P, N, S, Ca and Mg are considered to be the main constraints limiting plant growth and sustainable crop yields in acid soils [7,8]. High contents of Al and Fe cause extreme P fixation, which decreases the availability and use efficiency of soil P by the crops [9]. Phosphorus can be strongly adsorbed on the soil surfaces by forming chemical bonds with oxides and hydroxides of Fe and Al in acidic soils. Besides, Al toxicity primarily causes stunting of the primary root, inhibition of cell elongation and lateral root formation [10]. Poor root growth impaired nutrients and water uptake, making plants more susceptible to drought stress [11].

Bread wheat (*Triticum aestivum* L.) is one of the most important cereal crops playing a vital role in the country's economy, food security, and consumption. In Ethiopia, wheat covers an estimated area of 1.7 million ha with total annual grain production of 4.6 million tons by 4 million smallholder farmers [5]. In terms of area of production, wheat ranks fourth after *tef* (*Eragrostis tef* [Zucc.] Trotter), maize (*Zea mays* L.) and Sorghum (*Sorghum bicolor* L.) and third in total grain production after *tef* and maize in Ethiopia [5]. However, the productivity of wheat is still low with a national average yield of 3 t ha^{-1} compared to yields obtained from the research stations, i.e., 5 t ha^{-1} [12]. Soil nutrient deficiency associated with severe soil acidity [13] and low nutrient inputs application are among the primary drivers of low wheat yields in the highlands of Ethiopia [14].

Liming has been considered an effective method to mitigate soil acidity, increase soil pH, nutrient availability, and crop yields [15, 16]. Previous studies revealed that lime application significantly decreased exchangeable and soluble aluminium levels and increased soil pH, available soil nutrients such as P, N, exchangeable Ca and Mg [2]. Furthermore, lime application enhances microbial activities, organic matter mineralization, availability and uptake of nutrients [17–19]. Liming with optimal rate also substantially improves soil structure by binding the soil particles into more stable aggregates [19,20].

However, the practice of liming by smallholder farmers is meagre in the study area due to its high cost and limited supply. Thus, developing feasible mechanisms that can minimize the lime amount for resource-poor farmers is necessary. Information about the optimum lime rate to be applied is so far lacking. Moreover, there has been limited study about effects of row and broadcast lime application methods on acidic Luvisol of *Farta* district and wheat yields. Therefore, the objective of this study was to evaluate the effects of lime rate and method of application on properties of acidic Luvisol and wheat yields in north-western Ethiopia.

2. Materials and methods

2.1. Study area description

An on-farm experiment was conducted during 2018 and 2019 main cropping seasons at *Sahirna* village, *Farta* District of South Gondar Zone, in Amhara National Regional State (Fig. 1). The study area is geographically placed between 11°45′34″ to 11°48′25″ N latitude and 38°4′ 3″ to 38°6′14′ E longitude. The altitude of the district varies between 1900 and 4035 m above sea level. Regarding

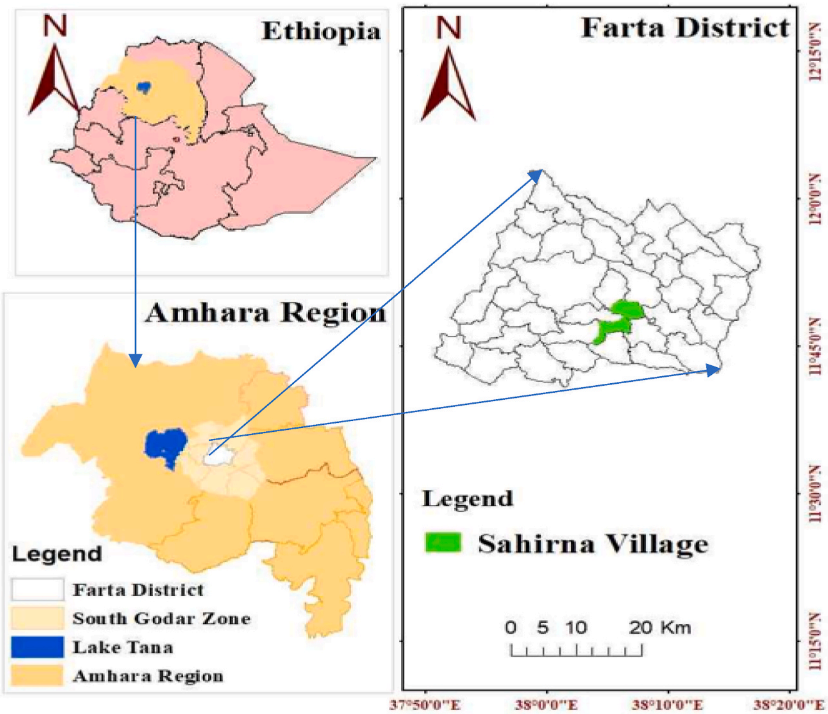

Fig. 1. Location map of the study area.

the topography, 45% is a gentle slope, while 29 and 26% are characterized by flat and steep slope lands, respectively. Based on 20 years (2000–2019) of climatic data collected from Amhara Meteorology Service Agency, the minimum, maximum, and average temperatures are 9.52, 22.95 and 15.8 °C, respectively. In addition, the study area has mean annual precipitation of 1482.30 mm. Rainfall distribution in the area is unimodal, and the main rainy season extends from May to September (Fig. 2).

Based on the information obtained from *Farta* District Office of Agricultural (unpublished), land use types of the district consist of arable land (64.7%), grazing (10.2%), forests, and shrubs (0.6%), settlement (7.8%) and wetlands (16%). The farming practice is described as a subsistence crop-livestock mixed system. Barely (*Hordeum vulgare*), wheat (*Triticum aestivum*), *tef* (*Eragrostis tef* [Zucc.] Trotter), potato (*Solanum tuberosum*) and faba bean (*Vicia faba* L.) are the principal crops growing in the area. The major soil types in the area are Alisols, Nitisols, Luvisols, Vertisols, Cambisols, Regosols and Lepthosols (Abayneh, 2017). The field experiments were conducted on dystric Luvisol which is the dominant soil type but strongly acidic and deficient in major plant nutrients that leads to low crop production in the study area.

2.2. Experimental set up

This on-farm field experiment was conducted during 2018 and 2019 main cropping seasons. The treatments included control, four lime rates applied as drilling along the row (0.5, 1, 2 and 3 t ha^{-1} lime) and four lime rates applied in broadcast method (2, 3, 6 and 12 t ha^{-1} lime). The treatments were selected using buffer pH and exchangeable acidity lime rate determination methods. The field experiment was arranged in a randomized complete block design (RCBD) with three replications. The treatments and application rates are presented in Table 1. The spacing between rows, plots and blocks were 0.2, 0.5 and 1 m, respectively. Gross plot size was 2.4 m × 2.5 m (6 m^2), accommodating 12 rows spaced at 20 cm. The net plot size was 1.6 m × 1.7 m (2.72 m^2) leaving one outermost row on both sides of each plot and 0.2 m row length at both ends of rows as borders.

FEAR = full dose of lime determined using exchangeable acidity method and applied in rows; FEAB = full dose of lime determined using exchangeable acidity applied in broadcasting method; FBR = full dose of lime determined using buffer method and applied in rows; FBB = full dose of lime determined using buffer method and applied in broadcasting method.

2.3. Lime rate determination

The rates of lime used for this experiment were quantified using exchangeable acidity and Buffer pH methods. For the exchangeable acidity method, the required amount of lime was calculated based on soil mass per 15 cm hectare-furrow-slice, soil bulk density and exchangeable Al^{+3} and H^{+} of each site. Assuming that 1 mol of exchangeable acidity would be neutralized by an equivalent mole of $CaCO_3$. The amount of lime applied using exchangeable acidity was calculated based on the following formula [21].

$$LR = \frac{\text{EA x BD x Depth (m)} \times 10^4 \text{m}^2 \times 1000}{2000} \tag{1}$$

where LR = Lime requirement ($CaCO_3$ kg $^{-1}$); EA is exchangeable acidity of the soil in cmol $(_+)$ kg^{-1}; BD is bulk density of the soil in Mg m^{-3} and depth is the depth of the plow layer (0.15 m).

Regarding the SMP-buffer pH lime requirement determination, the soil buffer pH value (5.4) was initially determined using the SMP buffer solutions. Then, the lime rate was estimated by relating the initial soil buffer pH value to a target pH of 6 as established by

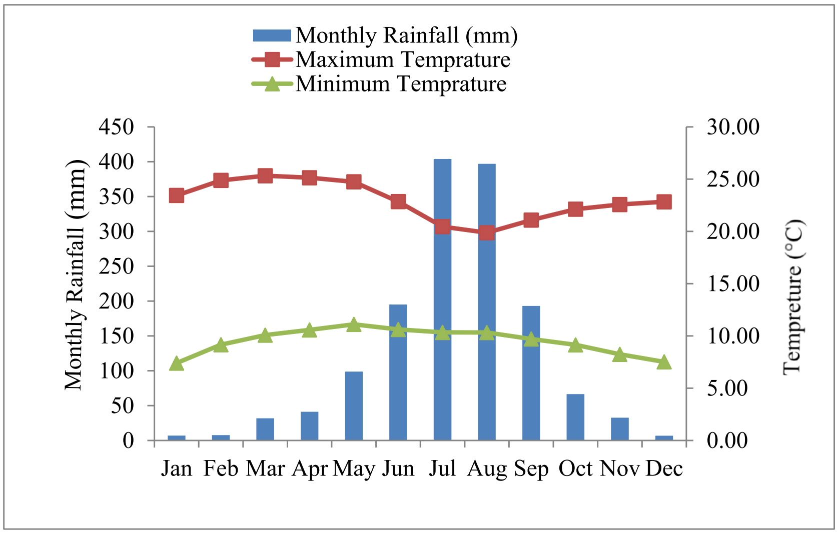

Fig. 2. Long-term (2000–2019) average rainfall and temperature of Farta District.

Table 1
List of treatments set up.

No.	Treatments	Descriptions
1	Control	Without lime
2	¼ FEAR	0.5 t ha^{-1} = Drill along the row
3	½ FEAR	1 t ha^{-1} = Drill along the row
5	FEAR	2 t ha^{-1} = Drill along the row
7	¼ FBR	3 t ha^{-1}=Drill along the row
4	FEAB	2 t ha^{-1} = Broadcast application
6	¼ FBB	3 t ha^{-1} = Broadcast application
8	½ FBB	6 t ha^{-1} = Broadcast application
9	FBB	12 t ha^{-1} = Broadcast application

Ref. [22], on which most nutrients become available for plant uptake.

2.4. Cultural practices

The experimental field was plowed four times based on farmers' conventional farming practices. A bread wheat variety named *Tay* was used as a test crop, as this variety is widely promoted and used in the study area. The recommended seed rate of 100 kg ha^{-1} was hand drilled in each plot. Agricultural lime (94% calcium carbonate equivalent) from Dejen lime stone crushing factory was used as a source of liming material. For broadcasting, the rate of lime was uniformly distributed by hand and incorporated into soils from 7 to 10 cm depth. Regarding row application, the recommended rate of lime was applied along the wheat seed rows per treatment. The recommended mineral fertilizers (100 kg ha^{-1} NPSB (18.7 N + 37.7 P_2O_5 + 6.95 S + 0.1 B) and 200 kg ha^{-1} urea (92 kg N), respectively) were applied uniformly to all treatments. Urea was applied in two splits (half at sowing and half at knee height) by considering the soil moisture condition, while the entire rate of NPSB was applied once at sowing.

2.5. Soil sampling and laboratory analysis

Initially, to evaluate the inherent soil nutrient status of the experimental plots, composite soil samples were collected before sowing using an Edelman auger at a depth of 0–20 cm. About ten soil samples were randomly collected from each experimental site and bulked together and homogenized to make a composite soil sample. Lastly, to determine changes in soil properties caused by treatment application, composite soil samples were collected from each plot per replications after harvest. Five sub-soil samples were collected from each treatment plot and properly homogenized to make a composite soil sample. The collected composite soil samples were labeled correctly, placed in plastic bags and transported to the laboratory for analysis. Later, the soil samples were air-dried and properly crushed to pass through a 2 mm sieve to analyze soil pH, texture, available phosphorus, exchangeable bases, and CEC, while some portion of the soil samples were passed through a 0.5 mm sieve for organic carbon and total nitrogen determinations. Soil samples (before sowing and after harvest) were analyzed at Horticoop soil analysis laboratory following the standard laboratory procedures.

Soil texture was analyzed with the Bouyoucos Hydrometer method [23]. Soil bulk density was determined using a core sampler method, oven-dried at 105 °C for 24 h [24]. Soil pH-water was measured potentiometrically with a pH meter in the supernatant suspension of 1:2.5 soil to water ratio [25]. The TN was determined using the micro-Kjedahl method [26]. The SOC content was analyzed by the Walkley-Black rapid extraction and titration method [27]. Available P was determined following the sodium bicarbonate ($NaHCO_3$) extraction method [28]. Exchangeable Ca, Mg, K, Na and available S were analyzed by the Mehlich-3 method [29]. The CEC was measured after extracting the soil sample with 1 M ammonium acetate (NHOAC) as outlined by Ref. [25]. Exchangeable acidity was determined using 1 M KCl extraction and with 0.02 M NaOH titration method as outlined by Ref. [30]. Likewise, the exchangeable Al was determined from the same extract by application of 1 M NaF which develop a complex with Al and released NaOH and then NaOH was back titrated with a standard solution of 0.02 M HCl.

2.6. Agronomic data collection

Agronomic data such as plant height, spike length, number of kernels per spike, total biomass, grain yield, straw yield and harvest index were collected using the following procedures:

Plant height (PH) was measured 120 days after sowing from the soil surface to the base of the spike on 10 randomly selected plants from the central unit area using a measuring tape. Spike length (SL) was measured for 10 randomly sampled plants in the harvestable rows, following the measurement from its base to the tip excluding awns. The mean number of kernels per spike (number/spike) was determined from 10 randomly selected spikes from the net plot areas. Biomass yield (BY) was measured by weighing the total above ground plant biomass within each central row of 1 m^2. Grain yield was measured using electronic balance and then adjusted to 12.5% moisture and converted to a hectare basis. Straw yield was calculated as the difference between above-ground biomass and grain yield. Thousand Grains Weight (TGW) sampled at random from the total grain harvest of the experimental plot was recorded using an analytical balance and expressed in gram/kg. Harvest Index (HI) was computed as the ratio of grain yield (GY) to biomass yield (BY) yield.

2.7. Data analysis

The influence of treatments on soil properties and crop attributes were statistically analyzed using analysis of variance (ANOVA) with Statistical Analysis System (SAS) software version 9.2 (SAS Institute [31]). When ANOVA result showed significant difference among treatments for each parameter, least significant difference (LSD) test at 5% probability level was applied for means separation. Moreover, correlation analysis was also carried out between soil properties and crop yields.

2.8. Economic analysis

Partial budget analysis was performed according to CIMMYT methodology [32] to determine the costs and benefits of treatments. The local costs of urea fertilizer (15.20 kg^{-1}), NPSB (15.40 Birr kg^{-1}), lime (2 Birr kg^{-1}), and labor cost (150 Birr day^{-1}) were used to estimate the total variable costs. Labor cost was calculated as man per day by recording the time required to complete the activities (furrow making and lime application). Grain and straw yields were reduced by 10% to consider variations between farmers and research fields. Gross field benefits were quantified by multiplying wheat grain and straw yields with their present costs (15.80 and 1.0 Birr kg^{-1}, respectively). The net benefit was estimated by deducting total variable costs from gross benefit. Then, treatments were arranged in increasing order of total variable costs. Dominated treatments were removed from the marginal rate of return (MRR) analysis. Lastly, MRR was estimated using the formula stated below [32]:

$$\text{MRR}(\%) = \frac{\text{Marginal increase in gross margin}}{\text{Marginal increase in variable cost}} \times 100 \quad (2)$$

3. Results and discussion

3.1. Characteristics of the experimental soil before planting

Data presented in Table 2, depicts that the study soil was clay loam with a percentage distribution of 45.9% clay, 32.7% silt, and 21.4% sand. The soil was strongly acidic, low in soil organic carbon (SOC), total nitrogen (TN) and available phosphorus (AP), according to the rating given by Ref. [33]. Besides, the contents of exchangeable Ca, Mg, K, and cation exchange capacity (CEC) were medium, while exchangeable Na was very low [34].

3.2. Effects of lime application on selected chemical properties of the soil

The results show that application of lime rates significantly affected soil chemical properties (Table 3). Application of mineral fertilizers alone decreased soil pH and increased exchangeable aluminum contents. Conversely, lime application noticeably increased the soil pH and decreased exchangeable aluminum. Our results revealed that treatments that received the highest dose of lime (12 t ha^{-1}) resulted in the highest values of soil pH (6.27), and the lowest exchangeable acidity and exchangeable Al (0.15, and 0.06 cmol $(_{+})$ kg^{-1}, respectively). On the other hand, the lowest soil pH (4.89), the highest exchangeable acidity and exchangeable Al (2.11, and 1.30 cmol $(_{+})$ kg^{-1}, respectively) were recorded from the control plots. Application of FBB, ¼ FBR and FEAR treatments increased soil pH by 29, 22 and 14.81%, respectively, compared to the control. Compared to the control, FBB, ¼ FBR and FEAR treatments significantly decreased exchangeable Al by 95.38, 93.85 and 54.62%, respectively. Moreover, compared to the control, exchangeable

Table 2
Characteristics of Luvisol before the experiment.

Parameters	Soil	Rating	References
Sand (%)	21.40	–	
Silt (%)	32.70	–	
Clay (%)	45.90	–	
Textural Class		Clay loam	[35]
BD (g cm^{-3})	1.32	Optimum	[36]
Exch. Ac (cmol $(_{+})$ kg^{-1})	2.04	–	–
Exch. Al (cmol $(_{+})$ kg^{-1})	1.26	High	[37]
Soil pH (water: soil, 1:2.5)	4.97	Strongly acidic	[33]
SOC (%)	2.11	Low	[33]
TN (%)	0.14	Low	[37]
AP (mg kg^{-1})	8.50	Low	[33]
Ca^{2+} (cmol $(_{+})$ kg^{-1})	8.17	Medium	[34]
Mg^{2+} (cmol $(_{+})$ kg^{-1})	1.45	Medium	[34]
K^{+} (cmol $(_{+})$ kg^{-1})	0.28	Medium	[34]
Na^{+} (cmol $(_{+})$ kg^{-1})	0.09	Very low	[34]
CEC (cmol $(_{+})$ kg^{-1})	22.93	Medium	[34]

BD = bulk density; soil pH = soil reaction; Exch. Ac = exchangeable acidity; Exch. Al = exchangeable aluminium; SOC = soil organic carbon; TN = total nitrogen; AP = available phosphorus; Ca^{2+}, Mg^{2+}, K^{+} and Na^{+} = exchangeable calcium; magnesium; potassium and sodium respectively CEC = Cation exchange capacity.

Table 3
Effects of lime rates on selected chemical properties of acidic Luvisol.

Treatments	pH (H_2O)	Exch. Ac (cmol (+) kg^{-1})	Exch. Al (cmol (+) kg^{-1})	SOC (%)	TN (%)	AP (mg kg^{-1})	Exchangeable bases (cmol (+) kg^{-1})				CEC (cmol (+) kg^{-1})
							Ca	Mg	K	Na	
Control	4.86^{f}	2.11^{a}	1.30^{a}	2.13^{c}	0.14^{d}	8.42^{d}	7.96^{d}	1.43^{c}	0.25^{c}	0.07	22.30^{d}
¼ FEAR	5.20^{ef}	1.83^{b}	1.16^{b}	2.18^{bc}	0.15^{cd}	8.98^{cd}	8.39^{d}	1.46^{c}	0.26^{c}	0.07	23.38^{cd}
½ FEAR	5.31^{de}	1.52^{c}	0.99^{c}	2.21^{bc}	0.17^{bcd}	9.53^{cd}	8.80^{cd}	1.51^{bc}	0.27^{c}	0.07	23.94^{cd}
FEAR	5.58^{cd}	1.04^{de}	0.59^{e}	2.25^{abc}	0.18^{abcd}	10.79^{abc}	10.40^{bcd}	1.56^{abc}	0.28^{bc}	0.08	25.52^{bcd}
¼ FBR	5.93^{ab}	0.51^{f}	0.08^{g}	2.34^{ab}	0.22^{ab}	12.01^{ab}	13.04^{ab}	1.74^{ab}	0.35^{ab}	0.08	28.12^{abc}
FEAB	5.40^{cde}	1.25^{d}	0.81^{d}	2.20^{bc}	0.16^{cd}	9.90^{bcd}	9.29^{cd}	1.49^{cd}	0.28^{bc}	0.08	24.67^{cd}
¼ FBB	5.67^{bc}	0.84^{e}	0.28^{f}	2.29^{abc}	0.19^{abc}	11.18^{abc}	11.67^{abc}	1.68^{abc}	0.32^{abc}	0.09	27.25^{abc}
½ FBB	6.05^{a}	0.32^{fg}	0.10^{g}	2.34^{ab}	0.21^{ab}	12.30^{a}	13.62^{a}	1.80^{a}	0.35^{ab}	0.09	30.03^{ab}
FBB	6.27^{a}	0.15^{g}	0.06^{g}	2.40^{a}	0.23^{a}	12.72^{a}	14.21^{a}	1.78^{ab}	0.37^{a}	0.09	31.40^{a}
p-value	0.001	0.001	0.001	0.055	0.012	0.010	0.001	0.030	0.016	0.062	0.012
LSD (0.05)	0.36	0.22	0.10	0.17	0.05	2.32	2.96	0.25	0.07	0.02	4.90
CV (%)	3.75	11.83	9.51	4.32	14.93	12.67	15.94	9.24	13.23	11.32	10.86

acidity decreased by 92.89, 75.83 and 50.71% under FBB, ¼BFR and FEAR treatments, respectively. Overall, the soil pH increased and exchangeable acidity and exchangeable Al^{3+} decreased with increasing lime rates. However, lime rates estimated by buffer pH method are higher in ameliorating soil acidity than the exchangeable acidity method. This result suggests that a greater lime rate is required to maintain optimum soil pH for plant growth which could be unaffordable to purchase large quantities of lime for smallholder farmers.

Likewise [2], reported that liming increased soil pH associated with increased concentrations of exchangeable cations such as Ca, Mg and K but decreased the amount of exchangeable Al compared to treatments without lime. Besides, lime application increased soil pH which might be due to the precipitation of exchangeable Al and Fe as insoluble hydroxides of Al and Fe [38]. [17] also found that lime application at a rate of 8 t ha^{-1} increased the soil pH from 4.1 to 5.7. Previous studies conducted in southern Ethiopia by Ref. [39] also revealed that soil pH raised from 5.03 to 6.72 and exchangeable acidity significantly decreased due to the application of 3.75 t lime ha^{-1} on Nitisols with high P fixation. However, this study showed that the broadcasting application of lime rates determined by exchangeable acidity could not maintain the desired levels of soil pH and exchangeable aluminum (Table 3). The reason could be lime rates quantified with exchangeable acidity method is low and unable to effectively neutralize soil acidity from the exchange sites [40]. Our result is in agreement with the findings of [21], who found that the application of 3 t ha^{-1} lime in strongly acidic soil was not enough to raise the soil pH above 5.5 and decrease the exchangeable acidity below 0.8 cmol kg^{-1}, which are favorable for wheat production. On the other hand [41], reported that applying 25% lime along the row is an effective option to ameliorate soil acidity and increase crop yield [40] also found that lime application through broadcasting method is less effective and not economical for smallholder farmers.

FEAR = full dose of lime determined using exchangeable acidity method and applied in rows; FEAB = full dose of lime determined using exchangeable acidity applied in broadcasting method; FBR = full dose of lime determined using buffer method and applied in rows; FBB = full dose of lime determined using buffer method and applied in broadcasting method; pH = soil reaction; Exch. Ac = exchangeable acidity; Exch. Al = exchangeable aluminum; SOC = soil organic carbon; TN = total nitrogen; AP = available phosphorus; Ca^{2+}, Mg^{2+}, K^{+} and Na^{+} = exchangeable calcium; magnesium; potassium and sodium respectively; CEC = cation exchange capacity.

The results showed that lime application significantly increased the status of soil AP and TN compared to treatments without lime (Table 3). However, the SOC content was not significantly affected by the application of treatments. Therefore, the highest contents of SOC (2.40%), TN (0.23%) and AP (12.72 mg kg^{-1}) were observed from treatments that received the maximum dose of lime. Compared to the control, soil AP increased by 51.07, 42.64, 28.15 and 13.18% under FBB, ¼ FBR, FEAR and ½ FEAR treatments, respectively. Likewise, soil TN increased by 64.28, 57.14, 28.57, and 14.29% under FBB, ¼ FBR, FEAR and ½ FEAR treatments, respectively, compared to the control.

In agreement with our results, [42, 54] reported that lime addition markedly increased soil AP contents due to increased soil pH, decreased Al^{3+} and Fe^{3+} ions and thereby reduced P fixation as Al–P and Fe–P. Moreover, liming increased the contents of AP, SOC and TN may be associated to the greater addition of organic inputs from crop residues and plant roots [42]. Lime application can also increase microbial activities and hasten the mineralization of organic matter, which in turn increases the levels of available P [2]. Similarly [43], found that liming increased soil pH from 6.1 to 6.6, resulting in greater release of available P ranging from 15.1 to 17.3 mg kg^{-1} compared to plots without lime with 4.2–7.1 mg P kg^{-1} and a pH value of 4.8.

Plots treated with lime rates significantly increased the concentrations of exchangeable Ca, Mg and K compared to treatments without liming (Table 3). The highest exchangeable Ca, Mg, and K (14.21, 1.80 and 0.37 cmol (+) kg^{-1}, respectively) were recorded from plots received the highest dose of lime. Compared to the control, exchangeable Ca of the soil increased by 78.52%, 63.82%, 30.65% and 10.55%, respectively, under FBB, ¼ FBR, FEAR and ½ FEAR treatments. The increase in exchangeable bases such as Ca and Mg with increasing lime rates could be related to their release from the liming material [44]. Our result is in line with the finding of [15,45], who reported that surface application of lime significantly increased soil pH, exchangeable Ca^{2+} and Mg^{2+} but decreased the exchangeable Al in acidic soils. Moreover [2,46], reported that lime application increased soil pH and exchangeable base cations such as calcium and magnesium and decreased exchangeable Al contents.

Similarly, cation exchange capacity (CEC) of the soil was significantly ($p < 0.05$) affected by the application of lime rates. The highest and lowest contents of CEC (31.40 and 22.30 cmol kg^{-1}), respectively were observed from treatments that received the highest dose of lime and the control plots. Compared to the control, the content of CEC was increased by 40.80%, 26.10% and 14.40% under FBB, ¼ FBR and FEAR treatments, respectively. In agreement with our findings, previous studies reported that liming markedly increased the contents of soil CEC, which might be associated with increased soil pH and higher concentrations of exchangeable base cations [18]. Similarly [47], demonstrated that the highest (33.34 cmol kg^{-1}) and lowest (19.18 cmol kg^{-1}) CEC contents were observed from plots treated with the highest lime rate and the control, respectively.

3.3. Effects of lime application on growth, yield and yield components of wheat

Application of increasing rates of lime significantly ($p < 0.05$) increased growth and yield attributes of wheat compared to plots without liming. The results showed that lime rates incorporated along row gave higher wheat yields compared to the broadcast application of the same lime rate in both years. However, applying the same lime rate within the row and broadcast did not show significant difference in yields of wheat. In general, the two years average results indicated that the highest wheat plant height (112.30 cm), spike length (10.82 cm), biomass (10.50 t ha^{-1}), grain (4.21 t ha^{-1}) and straw yields (6.26 t ha^{-1}) were obtained from plots amended with the highest lime rate. On the other hand, the lowest average plant height (94.11 cm), spike length (7.93 cm), biomass (6.96 t ha^{-1}), grain (2.57 t ha^{-1}) and straw (4.38 t ha^{-1}) yields of wheat were recorded from the control plots. Our results indicated that wheat plant heights increased by 19.32, 13.05, and 7.61%, and spike lengths by 36.44, 24.08, and 16.14%, respectively, under FBB, ¼ FBR and FEAR treatments compared to the control (Table 4). Biomass yields of wheat also increased by 50.86, 39.51, and 18.67%, and grain yields were by 63.81, 49.03 and 26.07% under FBB, ¼ FBR, and FEAR treatments, respectively. In general, wheat yield and yield components showed an increasing trend with increasing lime rate and time (Table 5). Consequently, the maximum wheat yields were obtained during the second year after the application of lime, implying that the lime efficiency was greater in the succeeding years than in the first year of its application.

FEAR = full dose of lime determined using exchangeable acidity method and applied in rows; FEAB = full dose of lime determined using exchangeable acidity and applied in broadcasting method; FBR = full dose of lime determined using buffer method and applied in rows; FBB = full dose of lime determined using buffer method and applied in broadcasting method.

Similarly [48], reported that application of 1.65 t ha^{-1} lime combined with 20 kg ha^{-1} phosphorus fertilizer increased barley grain yield by 274% compared with the control treatment [49] also found that lime addition at the rates of 1–5 t ha^{-1} showed about 45–81% faba bean yield increments over the control. The increase in wheat yields with addition of lime in the present study could be ascribed to the decrease in exchangeable Al and the increase in soil pH, organic matter and soil available nutrients [50]. Moreover, lime application along with mineral fertilizers noticeably increased crop yields by reducing the concentrations of acidic cations (Al^{3+} and H^{+}), increasing exchangeable base cations (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}) and phosphorus use efficiency in acidic soils [2]. Likewise [15,46], reported that the substantial increase in crop yields due to lime application was attributed to the reduction of exchangeable Al, increase in soil pH and greater concentrations of basic nutrients such as Ca, Mg and K. The other reason could be lime addition increased the response of crops to applied P fertilizer which can be otherwise unavailable to crops as a result of P fixation in acidic soils [48]. Ref. [51] proved that liming decreases nitrogen oxide (N_2O) emissions, thereby improving nitrogen use efficiency and crop yields. Besides, lime application overcomes Al toxicity, improves plant root growth, nutrients and water uptake from the soil and gives higher crop yields [52]. Table 6 shows that wheat grain yield was positively and significantly correlated with soil pH, AP, CEC and exchangeable Ca ($r = 0.60^{*}, 0.95^{**}, 0.89^{**}$ and 0.90^{**}, respectively). However, wheat grain yield was negatively corelated with exchangeable acidity and Al of the soil ($r = -0.75^{**}$ and 0.73^{**}, respectively).

In line with our results [45], found that crop yields were increased with increasing lime rates and time. Similarly [2], found that the highest yield of barley was recorded in the third experimental year following lime application which implies that the efficiency of lime could be more noticeable in the subsequent years than in the first and second years of its incorporation. However, studies demonstrated that lime application alone could not significantly increase crop yields [53] if the inherent soil nutrients are already depleted. Therefore, lime application improves crop yields when acidic soils comprise essential nutrients rendered unavailable to crops resulting from low soil pH.

Table 4
Effects of lime treatments on plant height and spike length of wheat.

Treatments	Plant Height (cm)			Spike Length (cm)		
	2018	2019	Average	2018	2019	Average
Control	94.25^{d}	93.97^{d}	94.11^{d}	7.95^{d}	7.89^{f}	7.93^{e}
¼ FEAR	95.03^{cd}	96.10^{d}	95.56^{d}	8.02^{cd}	8.27^{ef}	8.15^{de}
½ FEAR	96.12^{cd}	99.17^{cd}	97.64^{cd}	8.24^{cd}	8.51^{def}	8.38^{cd3}
FEAR	99.80^{bcd}	102.74^{bcd}	101.27^{bcd}	9.01^{abcd}	9.43^{cdef}	9.21^{bcde}
¼ FBR	104.72^{abc}	108.05^{abc}	106.39^{abc}	9.60^{abc}	10.08^{abc}	9.84^{abc}
FEAB	98.13^{cd}	100.88^{cd}	99.50^{cd}	8.53^{bcd}	8.97^{cdef}	8.75^{cde}
¼ FBB	100.89^{bcd}	103.78^{abcd}	102.33^{bcd}	9.36^{abcd}	9.85^{abcd}	9.60^{abcd}
½ FBB	108.06^{ab}	110.80^{ab}	109.45^{ab}	10.04^{ab}	10.62^{ab}	10.33^{ab}
FBB	110.90^{a}	113.71^{a}	112.30^{a}	10.50^{a}	11.14^{a}	10.82^{a}
P-value	0.019	0.008	0.012	0.031	0.003	0.010
LSD (0.05)	9.77	9.93	9.84	1.61	1.50	1.56
CV (%)	5.65	5.60	5.62	10.37	9.34	9.83

Table 5
Effects of lime treatments on yield and yield components of wheat.

Treatments	Biomass yield (t ha^{-1})			Grain yield (t ha^{-1})			Straw yield (t ha^{-1})		
	2018	2019	Average	2018	2019	Average	2018	2019	Average
Control	7.01^{d}	6.90^{e}	6.96^{e}	2.60^{d}	2.55^{e}	2.57^{d}	4.41^{e}	4.35^{d}	4.38^{d}
¼ FEAR	7.20^{d}	7.38^{de}	7.29^{de}	2.67^{d}	2.79^{de}	2.72^{d}	4.53^{de}	4.60^{cd}	4.57^{cd}
½ FEAR	7.54^{cd}	7.82^{cde}	7.68^{cde}	2.80^{cd}	2.96^{cde}	2.88^{cd}	4.74^{cde}	4.85^{bcd}	4.80^{bcd}
FEAR	8.14^{abcd}	8.37^{abcde}	8.26^{abcde}	3.16^{abcd}	3.32^{abcde}	3.24^{abcd}	4.98^{bcde}	5.06^{abcd}	5.02^{bcd}
¼ FBR	9.58^{abc}	9.85^{abc}	9.71^{abc}	3.75^{abc}	3.90^{abc}	3.83^{abc}	5.82^{abc}	5.96^{ab}	5.88^{ab}
FEAB	7.75^{bcd}	8.10^{bcde}	7.92^{bcde}	2.94^{bcd}	3.10^{bcde}	3.02^{bcd}	4.81^{bcde}	5.00^{abcd}	4.90^{bcd}
¼ FBB	9.16^{abcd}	9.42^{abcd}	9.29^{abcd}	3.48^{abcd}	3.65^{abcd}	3.56^{abcd}	5.68^{abcd}	5.77^{abc}	5.73^{abc}
½ FBB	9.95^{ab}	10.19^{ab}	10.07^{ab}	3.89^{ab}	4.12^{ab}	4.01^{ab}	6.05^{ab}	6.07^{ab}	6.06^{ab}
FBB	10.36^{a}	10.65^{a}	10.50^{a}	4.12^{a}	4.30^{a}	4.21^{a}	6.24^{a}	6.35^{a}	6.29^{a}
P-value	0.036	0.034	0.035	0.040	0.031	0.035	0.035	0.038	0.036
LSD (0.05)	2.25	2.37	2.31	1.02	1.10	1.05	1.24	1.29	1.27
CV (%)	15.43	15.78	15.60	18.27	18.54	18.40	13.78	14.14	13.94

FEAR = full dose of lime determined using exchangeable acidity method and applied in rows; FEAB = full dose of lime determined using exchangeable acidity and applied in broadcasting method; FBR = full dose of lime determined using buffer method and applied in rows; FBB = full dose of lime determined using buffer method and applied in broadcasting method.

Table 6
Correlation analysis between soil proprieties and wheat yield as affected by lime treatments.

Parameter	GY	pH	Exch. Ac	Exch. Al	AP	SOC	TN	Ca	Mg	K
pH	0.60*									
Exc. Ac	−0.75**	−0.92**								
Exc. Al	−0.73**	−0.90**	0.97**							
AP	0.95**	0.59*	−0.79**	−0.78**						
SOC	0.38	0.90**	−0.75**	−0.72**	0.30					
TN	0.25	0.87**	−0.76**	−0.77**	0.27	0.88**				
Ca	0.90**	0.81**	−0.85**	−0.84**	0.84**	0.67**	0.52*			
Mg	0.94**	0.60**	−0.73**	−0.74**	0.93**	0.38	0.25	0.91**		
K	0.27	0.69**	−0.70**	−0.72**	0.37	0.55*	0.79**	0.34	0.22	
CEC	0.89**	0.77**	−0.79**	−0.76**	0.80**	0.65**	0.45*	0.96**	0.87**	0.25

GY = Grain yield; pH = soil reaction; Exch. Ac = exchangeable acidity; Exch. Al = exchangeable aluminum; SOC = soil organic carbon; TN = total nitrogen; AP = available phosphorus; Ca^{2+}, Mg^{2+}, K^{+} and Na^{+} = exchangeable calcium; magnesium; potassium and sodium respectively; CEC = cation exchange capacity.

* Correlation significant at $p < 0.05$.

** Significant at $p < 0.01$.

3.4. Economic analysis

The data in Table 7 show that treatments that received 3 t ha^{-1} lime in-the-row gave the highest net benefit (52271.4 Birr ha^{-1} (1US $ = 36.7 ETB)) which is more feasible for smallholder farmers. The highest economic profit from this treatment could be related to the increase in soil properties (Table 3) and greater crop yields (Table 5). Conversely, the lowest net benefit (36727.2 Birr ha^{-1}) was observed under plots amended with the highest dose of lime followed by the control plots (40487.4 Birr ha^{-1}). Overall, the treatments received the highest lime rate was less profitable which can be resulting from less NB and greater TVC.

FEAR = full dose of lime determined using exchangeable acidity method and applied in rows; FEAB = full dose of lime determined using exchangeable acidity and applied in broadcasting method; FBR = full dose of lime determined using buffer method and applied in rows; FBB = full dose of lime determined using buffer method and applied in broadcasting method; TVC = total variable cost; GY = grain yield kg ha^{-1}; SY = straw yield; GB = gross benefits; NB = net benefits; D = dominance; MRR = marginal rate of return.

4. Conclusion

The present study shows that the application of mineral fertilizers decreased soil pH, exchangeable base cations (Ca^{2+} and Mg^{2+}), cation exchange capacity and increased acidic cations (Al^{3+}). On the other hand, application of lime significantly increased soil pH, available phosphorus, exchangeable base cations and decreased exchangeable Al^{3+}. Higher increase in soil pH, available soil nutrients and reduction of exchangeable aluminum were observed from buffer pH lime rates than that of exchangeable acidity. Besides, lime application along the row is more effective in mitigating soil acidity, enhancing available nutrients and crop yields compared to broadcast lime application. Lime rates determined by the exchangeable acidity method cannot maintain the desired levels of soil pH, exchangeable acidity and aluminum. The result showed that the highest wheat grain yields were achieved from the application of 12 t ha^{-1} lime due to the mitigation of soil acidity. However, from an economic point of view, the application of 3 t ha^{-1} lime along the row is found to be more affordable and profitable for smallholder farmers in the study area. Therefore, we conclude that applying 3 t ha^{-1}

Table 7
Economic analysis of lime rates on wheat productivity.

Treatments	TVC (Birr ha^{-1})	GY (kg ha^{-1})	SY (kg ha^{-1})	GB (Birr ha^{-1})	NB (Birr ha^{-1})	MRR (%)
Control	0	2295	3978	40239.0	40487.4	
¼ FEAR	1350	2448	4122	42800.4	41450.4	89.7
½ FEAR	2550	2592	4338	45291.6	42741.6	107.6
FEAB	4800	2718	4410	47354.4	42554.4	D
FEAR	4950	2916	4518	50590.8	45640.8	2057.6
¼ FBB	7200	3204	5157	55780.2	48580.2	130.6
¼ FBR	7350	3438	5301	59621.4	52271.4	2460.8
½ FBB	14,400	3609	5454	62476.2	48076.2	D
FBB	28,800	3789	5661	65527.2	36727.2	D

lime is the best option for smallholder farmers to ameliorate soil acidity, improve nutrient availability and crop yields in the study area and others having similar environment. However, to determine the residual effects and reapplication of lime, the long-term effects of lime rates on soil acidity and crop yields need to be investigated through further research.

Declarations

Author contribution statement

Workineh Ejigu: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Yihenew G. Selassie: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Eyasu Elias; Eyayu Molla: Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interest's statement

The authors declare no conflict of interest.

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