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Effects of lime and phosphorous application on chemical properties of soil, dry matter yield, and phosphorus concentration of barley (*Hordeum vulgare*) grown on Nitosols of Emdibir, Southern Ethiopia

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The effects of lime and P fertilizer application on chemical properties of acid soil, and dry matter yield (DMY) and phosphorus concentration of barley were investigated in a greenhouse experiment in 2013. The experimental soil was collected from Emdibir, South-Western Ethiopia. Five lime levels (CaCO$_3$) (0, 6093, 12186, 18280, and 24373 mg CaCO$_3$ kg^{-1} soil) in a factorial combination with five phosphorus (TSP) rates (0, 300, 600, 900 and 1600 mg kg^{-1}) were used. The treatments were replicated three times. Barley, variety HB-1307, was used as a test crop. All the soil and plant analysis was conducted following standard laboratory procedures. The soil chemical properties, except Mg, were significantly (P≤0.05) affected by increasing rates of lime and/or P addition. The highest lime rate resulted in an increase in soil pH, exchangeable Ca and Cu, and a decrease in the levels of exchangeable acidity and Al, Fe, Mn, and Zn. The DMY and plant P of barley were increased with the lime rate. The lime and P interaction effects were significant (P≤0.05) on exchangeable Ca, Al, and DMY. Optimum lime (12186 mg kg^{-1}) application has a decreasing effect on P fixation by Fe and Al. While the optimum lime rate in combination with the highest rate of P enhanced fixation by Ca. The change in soil chemical properties and DMY might encourage better barley growth on this soil. In conclusion, lime application beyond 18280 mg CaCO$_3$ kg^{-1} soil may not be beneficial for the soil chemical properties and barley DMY.

Key words: Chemical properties, dry matter yield, soil exchangeable acidity, phosphorus concentration phosphorus fixation.

INTRODUCTION

Soil acidity, which is a complex process resulting in the formation of acid due to excessive concentration of non-soluble and toxic ions in the soil solution is an impediment to agricultural production in areas where

heavy rainfall is causing a nutrient loss through leaching and soil erosion. In the context of agricultural problem soils, acid soils are those in which acidity dominates the problems related to agricultural land use (Kamprath, 1984).

Crop yields in acid soils are frequently reduced by 50% and can drop to zero even under the application of optimum rate of NP fertilizers (Wassie and Shiferaw, 2011). Increased soil acidity may lead to reduced yields, poor plant vigor, uneven pasture, and crop growth, poor nodulation of legumes, stunted root growth, persistence of acid-tolerant weeds, increased incidence of diseases, and abnormal leaf colors. Increased acidity also leads to poor plant growth and water use efficiency due to nutrient deficiencies and imbalances, and/or induced aluminium and manganese toxicity (Fox, 1979; Kisinyo et al., 2014; Marschner, 2011).

Soil acidity is a serious threat to crop production in most highlands of Ethiopia in general and in Southern Nations Nationalities and Peoples' Region (SNNPR) in particular (Desta, 1987; Abdenna et al., 2007). In SNNPR, the highlands of Gamugofa, Sidama, Kembata, Hadya, and Guragie areas are severely affected by soil acidity (Wassie and Shiferaw, 2008). In some barley and wheat growing areas of central and southern Ethiopia, farmers have shifted to producing oats, a crop more tolerant to soil acidity than wheat and barley (Abdenna et al., 2007). Emdibir, a village in the Gurage zone, southwest Ethiopia, is one of the sites affected by soil acidity. The increasing trend of soil acidity and exchangeable Al in arable and abandoned lands are attributed to intensive cultivation and continuous use of acid-forming inorganic fertilizers (Abdenna et al., 2007). The effect of soil acidity in the area is reflected well in the growth and yield of acid-sensitive crops, especially on barley. The poor performance of barley in the area might be due to acidity decreasing plant growth owing to the unavailability of nutrients (P, Ca and Mg) and toxicity of some trace elements (Eduardo et al., 2005).

To alleviate this problem, application of manure and intercropping or rotating cereals with legumes are common practices in the study area. However, farmers are recently focusing on crop cultivation rather than livestock production, and therefore, the amount of manure for crop production is decreasing from time to time. Hence, the application of lime in the form of $CaCO_3$, CaO, and Ca (OH)$_2$ is becoming an acceptable practice to reclaim acid soils. The main effect of liming is the neutralization of exchangeable H^+ and Al^{3+} and increasing the degree of base saturation and pH values. The decrease in exchangeable Al and Mn and the high reduction in Al activity in the soil solution are believed to be the main reasons for the frequently observed crop yield improvements as a result of liming acid soils (Haynes and Ludecke, 1981; Fegeria and Baligar, 2008; Rebecca et al., 2010). In the past, there was a massive campaign to demonstrate the beneficial effect of liming in ameliorating soil acidity on several crops of the area on farmers' fields, and encouraging results were obtained (Taye et al., 1996). Applying 3t lime and 30.3 kg P per ha was recommended at one site in the Cheha district of the Gurage Zone, wherein Emdibir is also found (Taye et al., 1996). However, information on the effects of liming on soil physical, chemical, and biological properties is not adequate. The objective of this greenhouse study was to determine the effects of lime and phosphorus fertilizer applications on selected chemical properties and phosphorus fixation of acid soil of Emdibir and dry matter yield of barley.

MATERIALS AND METHODS

Experimental site

A greenhouse experiment was conducted at the Holeta Agricultural Research Center in 2013. The soil was collected from Emdibir, Southwestern Ethiopia. Emdibir is located in the Gurage Zone of the Southern Nations, Nationalities, and Peoples' Region, at coordinate between 8°7′ to 8.11°N and 37°56′ to 37.93°E and elevation between 2130 and 2164 ms above sea level. The mean annual rainfall from a ten years data was about 1268.04 mm. The average maximum and minimum temperatures were 24.97 and 10.69°C, respectively. The dominant soil types of the area are Nitosols and Regosols having pH values ranging between 4.59 and 5.2 (HARC, 2011).

Experimental setup and treatment application

Random surface soil samples at 0-15 cm depth were taken using an Augur from farmers' fields from thirty different sites and mixed thoroughly to make a composite. The soil samples were air-dried, sieved to pass through 2 mm sieve. Samples were taken from the composite sample and analyzed for physical and chemical properties; particle size distribution was analyzed by the hydrometer method (Day, 1965). Soil bulk density was determined by the undisturbed core sampling method, while particle density was measured by the pycnometer method (Black, 1965). Total porosity was computed from the bulk density (Bd) and particle density (Pd) values as:

$$\text{Total porosity (\%)} = \left(1 - \frac{Bd}{Pd}\right) \times 100$$

The soil pH was measured using a digital pH meter in the supernatant suspension of 1:1 soil liquid ratio where the liquids were water and 1 M KCl solutions (Sahlemedhin and Taye, 2000). Exchangeable bases were extracted with 1M-ammonium acetates at pH 7. Exchangeable Ca and Mg were measured from the extract using atomic absorption spectrophotometer while exchangeable K and Na were determined from the same extract with a flame photometer. Percent base saturation (PBS) was calculated by dividing total exchangeable bases to the CEC of the soil and multiplied by 100. Cation exchange capacity (CEC) of the soil was determined by ammonium acitate method following the procedure described by Chapman (1965). Exchangeable acidity was determined by saturating the soil samples with potassium chloride solution and titrated with sodium hydroxide as described by McLean (1965) whereas effective cation exchange capacity (ECEC) was computed by the summation of exchangeable bases and exchangeable acidity. Organic carbon was determined following the

wet digestion method as described by Walkley and Black (1934) whereas the Kjeldahl procedure was followed for total nitrogen determination as described by Jackson (1958). Available phosphorus was determined both by Olsen and Bray II methods as indicated by Olsen et al. (1954) and Bray and Kurtz (1945), respectively. Phosphorus extracted with both methods was determined colorimetrically following Murphy and Riley (1962) procedure. Available Fe, Mn, Zn, and Cu were extracted with the DTPA method as described by Lindsay and Norvell (1978) and measured by atomic absorption spectrophotometer.

Fractionation of P involved sequential extraction by 0.1N NaOH 1M NaCl solution 0.3M, citrate bicarbonate, citrate bicarbonate dithionate, and 1N HCl to remove Fe and Al bound P, non-occluded Fe bound P, P occluded with Fe oxide and Ca-bound P, respectively. Phosphorus bound by Fe-Al and Ca was determined colorimetrically following chloromolybdic-boric acid method using stannous chloride as a reductant (Page et al., 1982). The composite sample taken from the area was filled in a plastic pot by weighing 3 kg soil and arranged in a completely randomized design (CRD) with five levels of lime (0, 2.03, 4.06, 6.09, and 8.12 g $CaCO_3$ kg^{-1} soil) and five levels of P (0, 0.1, 0.2, 0.3 and 0.5 g P kg^{-1} soil) and replicated three times. The lime requirement (LR) of the experimental soil was determined based on acid saturation of the soil, taking into account the amount of lime needed to neutralize the acid content (Al + H) of the soil up to the permissible acid saturation level for barley growth. The initial acid saturation of the experimental soil was calculated as the percentage of the exchangeable acidity (exchangeable Al + H) to the effective cation exchange capacity (ECEC) (exchangeable Ca + Mg + K + Na + Al + H). The amounts of exchangeable acidity (Al + H) and ECEC of the experimental soil were determined from the composite soil sample collected from farmers' fields. The permissible acid saturation(PAS) value was taken as 10% (Manson and Katusic, 1997). Finally, the acid saturation (AS) value of the experimental soil in excess of the PAS for the barley was considered as the amount of acidity that needs to be neutralized by the application of lime and so determined as the LR.

Since the neutralizing value of the lime used was 75% of pure $CaCO_3$; the lime requirement factor was approximately 3000 kg lime ha^{-1} cmol^{-1} of acidity to be eliminated. Thus, the quantity of lime required (LR) for the soil in the study area was estimated as:

LR = 3000 (AS - PAS) / 100 × ECEC

Accordingly, the applied lime rates were 0, 0.5, 1, 1.5, and 2 times the calculated lime requirement (LR) of the soil.

Triple superphosphate (TSP) was used as the source of P and the entire rates were mixed thoroughly with the soil at sowing. On the other hand, $CaCO_3$ with a purity of 75% was used as the source of lime, and the whole doses of lime of the respective treatment were thoroughly mixed by hand a month before sowing. Fifty mg N kg^{-1} soil as urea, 60 mg K kg^{-1} soil as KCl, and 25 mg Mg kg^{-1} soil as $MgSO_4.7H_2O$ were added to each pot before sowing.

Barley, variety HB-1307, was used as a test crop. Twenty-five seeds were sown in each pot and thinned to 10 seedlings per pot after emergence. The pots were watered to field capacity regularly. Weeding was done as needed to keep weed-free pots and the plants were kept in the pots up to 50% heading (74 days after sowing).

Plant data collection

The above-ground parts of the barley plants were harvested at heading. Cutting was done at the soil surface and the materials were dried in an oven at 65°C for 48 h, weighed, and ground to pass through a 1 mm sieve, and saved for P content determination.

Data analysis

The soil chemical properties and agronomic data were subjected to analysis of variance (ANOVA) using the general linear model procedure of the statistical analysis system (SAS, 1999). The least significant difference (LSD) test was used to separate treatment means when the treatment effects were found significant at P≤0.05.

RESULTS AND DISCUSSION

Physicochemical properties of experimental soil

The textural class of the soil was clayey, with sand, silt, and clay proportions of 21.5, 28.5, and 50%, respectively (Table 1). Similarly, the bulk, particle density, and percent total pore space were 1.34 g/cm^3, 2.27 g/cm^3 and 40.71%, respectively (Table 1). Clay textural class soils are expected to have higher particle density but lower particle density result was obtained from the experimental soil, this might be due to the organic carbon content of the soil which is medium (Table 1), and particle density decreases as the organic carbon of the soil increases. These results show that the experimental soil has good soil aeration and permeability following the standard suggested by (Carter, 2002).

The experimental soil falls under the strongly acidic (pH 4.46) class having high exchangeable Al^{+3} content of 3.22 cmolkg^{-1} (Landon, 1991). Soils of the study areas are strongly acidic because of high precipitation of the area, which causes large leaching of bases down the soil profile (Foth and Ellis, 1997; Girma, 2001; Brady and Weil, 2016). Slattery et al. (1999) also indicated that in such soils wide ranges of plants can be affected by aluminium toxicity. Besides, phosphorus availability could also be affected due to fixation with aluminium. The available P content of the soil (7.0 mg kg^{-1} Olsen and 7.4 mg kg^{-1} Bray II) was low following the ratings of Pam and Brian (2007) (Table 1), whereas the total nitrogen and organic carbon contents of the soil are medium (Landon, 1991). The soil had a CEC of 23.91 cmol kg^{-1} and base saturation of 35.59%, which are low (Pam and Brian, 2007) indicating that the basic cations are severely removed by leaching and the fertility of experimental soil is low.

The lower level of basic cations might be due to the high rainfall of the area, in conditions where rainfall exceeds evapotranspiration or when rainfalls exceed 500 to 600 mm per annum, the basic soil cations (Ca, Mg, K) are gradually leached and replaced with cations held in colloidal soil reserves (Slattery and Hollier, 2002). On the other hand, the exchangeable Ca, Mg, and K contents of 5.37, 2.41, and 0.54 cmol kg^{-1} (Table 1) were in the medium range according to Pam and Brian (2007). The concentrations of the micronutrients (Fe, Mn, Cu, and Zn) in the soil were above their critical limits (Table 1) in accordance with the critical values indicated by Havlin et al. (1999) and such high values of the micronutrients might be attributed to the high solubility and availability of

Table 1. Physicochemical properties of the experimental soil before sowing.

Parameter	Value
Particle size distribution	
Sand (%)	21.5
Silt (%)	28.5
Clay (%)	50.0
Textural class	Clay
Bulk density (g cm^{-3})	1.34
Particle density (g cm^{-3})	2.27
Porosity (%)	40.71
pH (H_2O 1:1)	4.46
Exchangeable acidity (cmol(+)kg^{-1})	3.67
Exchangeable Al^{+3} (cmol(+)kg^{-1})	3.22
Exchangeable H^+ (cmol(+)kg^{-1})	0.45
Organic carbon (%)	4.47
CEC (cmol (+) kg^{-1})	23.91
ECEC(cmol(+)kg^{-1})	12.19
Acid saturation (%)	32.7
Total nitrogen (%)	0.35
Available phosphorus	
Bray II (mg kg^{-1})	7.4
Olsen (mg kg^{-1})	7.0
Exchangeable K (cmol (+) kg^{-1})	0.54
Exchangeable Na (cmol(+) kg^{-1})	0.19
Exchangeable Ca (cmol(+) kg^{-1})	5.37
Exchangeable Mg (cmol(+) kg^{-1})	2.41
Total exchangeable bases (cmol(+)kg^{-1})	8.51
Base saturation (%)	35.59
Available Fe (mg kg^{-1})	105.12
Available Mn (mg kg^{-1}	81.61
Available Cu (mg kg^{-1})	2.85
Available Zn (mg kg^{-1})	3.79

the elements that increase at low pH (Slattery and Hollier, 2002).

Soil pH, exchangeable acidity, and exchangeable aluminium as influenced by liming and P application

Soil pH

Soil pH increased significantly (P≤ 0.05) with increasing levels of applied lime (Figure 1). However, the application of phosphorus and its interaction with lime did not show a significant effect on soil pH. The highest soil pH (6.15) was recorded with the application of 24373 mg lime kg^{-1} soil followed by application of 18280 mg lime kg^{-1} soil (Figure 1). Applying the highest lime rate (24373 mg kg^{-1}) increased soil pH by 1.48 units over the control. Compared to the control an increase in soil pH was observed even with the application of half of the lime

required to neutralize the soil (6093 mg kg^{-1} soil). The results are in agreement with that of Mercy and Ezekiel (2007) which indicated that optimal liming at 50.0 mg kg^{-1} resulted in increasing soil pH from 6.1 to 6.6 in Nigeria. An increase in soil pH following the application of lime ($CaCO_3$) was also reported elsewhere in Ethiopia. For instance, Desta (1987) found that application of 3 ton lime/ha raised the pH from 4.8 to 6.3 after barley harvest at Bedi (Getachew et al., 2017) also observed that application of 2.2 t/ha lime increased soil pH from the initial 4.8 to 5. The increment of pH after lime application is due to the removal of hydrogen by calcium from lime ($CaCO_3$) that makes the pH to rise (Moody and Cong, 2008).

Exchangeable acidity (Al+H)

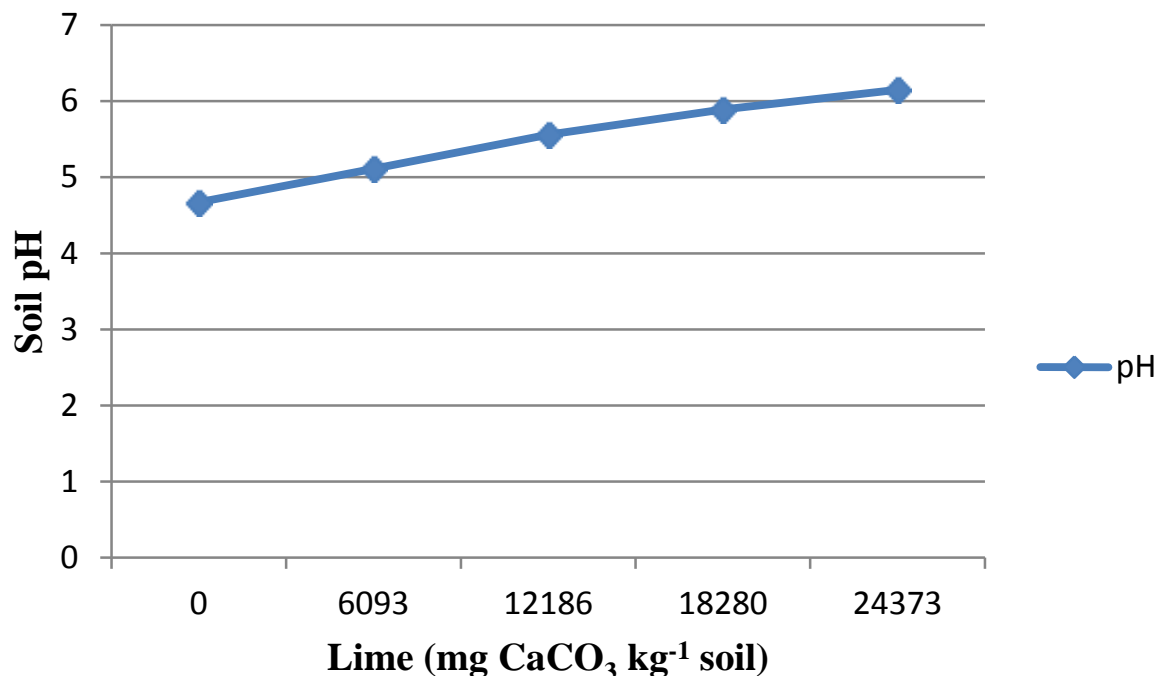Exchangeable acidity contents of the soil were

Figure 1. Effect of lime on pH values of acid soils after harvest.

Table 2. Effect of lime and phosphorus on soil exchangeable acidity (cmol kg^{-1}) after harvest.

Treatments (mg kg^{-1} soil)		Phosphorus					Lime mean
		0	300	600	900	1600	
	0	2.174[a]	2.333[a]	1.217[b]	1.355[b]	1.339[b]	1.683
	6093	0.485[cd]	0.273[de]	0.210[de]	0.160[de]	0.340[c]	0.294
Lime	12186	0.227[de]	0.123[e]	0.080[e]	0.110[e]	0.093[e]	0.127
	18280	0.060[e]	0.043[e]	0.073[e]	0.040[e]	0.080[e]	0.059
	24373	0.047[e]	0.030[e]	0.043[e]	0.037[e]	0.027[e]	0.037
P mean		0.598	0.561	0.325	0.340	0.376	-
LSD (0.05)				0.046			
CV (%)				13.54			

Main effect means within a column followed by the same letter(s) are not significantly different at P≤0.05.

significantly (P≤ 0.05) decreased with increasing rates of lime and P as well as by their interaction effects (Table 2). Application of lime at the highest rate (24373 mg kg^{-1} soil) in combination with the highest P fertilizer (1600 mg kg^{-1} soil) significantly (P ≤ 0.05) reduced soil exchangeable acidity to 0.027 cmol (+) kg^{-1}) compared to the highest mean exchangeable acidity (2.174 cmol (+) kg^{-1}) obtained from the control pots (Table 2). The reduction in exchangeable acidity with liming is explained by the increased replacement of Al by Ca in the exchange site and by the subsequent precipitation of Al as Al(OH)$_3$ (Havlin et al., 1999). Phosphorus additions as Ca(H$_2$PO$_4$)$_2$ also increased the exchangeable Ca content of the soil and thus the exchangeable Al form insoluble

Al(OH)$_3$ at high pH (Haynes and Ludecke, 1981). Similar lime by P interaction effects on exchangeable acidity was also reported by Haynes and Ludecke (1981) and Oluwatoyinbo et al. (2005).

Exchangeable aluminium

Exchangeable Al contents of the soil were significantly (P ≤ 0.05) decreased with increasing rates of lime and P as well as by the interaction effects of lime and P application (Table 3). The interaction of lime by P highly reduced the exchangeable aluminium content of the soil. Application of full dose of lime required to neutralize the soil (12186

Table 3. Effect of lime and phosphorus on exchangeable Aluminum cmol kg^{-1} of the soils after harvest.

Treatments (mg kg^{-1} soil)		Phosphorus					Lime mean
		0	300	600	900	1600	
	0	1.688^a	1.373b	1.227^c	1.179^c	1.060^d	1.305
	6093	0.050^e	0.043^e	0.040^e	0.037^e	0.023^e	0.039
Lime	12186	0.020^e	0.020^e	0.020^e	0.023^e	0.007^e	0.018
	18280	0.000^e	0.000^e	0.000^e	0.000^e	0.000^e	0.000
	24373	0.000^e	0.000^e	0.000^e	0.000^e	0.000^e	0.000
P mean		0.350	0.352	0.287	0.257	0.248	0.218
LSD (0.05)				0.023			
CV (%)				7.70			

*The main effect means within a column followed by the same letter are not significantly different at P≤0.05.

mg kg^{-1} soil) in combination with the highest P fertilizer (1600 mg P kg^{-1} soil) significantly reduced soil exchangeable Al to almost zero (Table 3). Considering the interaction effect of lime by P, the highest mean exchangeable Al (1.688 cmol(+) kg^{-1}) was observed in the control treatments while the lowest (0 cmol(+) kg^{-1}) were observed by the addition of 18280 and 24373 mg CaCO$_3$ kg^{-1} soil regardless of P application. This is explained by the increased replacement of Al by Ca in the exchange site and by the subsequent precipitation of Al as Al(OH)$_3$, when the soil was limed (Havlin et al., 1999). Furthermore, a clear decrease in exchangeable Al with increasing P rates is probably due to the formation of hydroxy-A1 phosphates (Havlin et al., 1999) and/or due to P additions as Ca(H$_2$PO$_4$)$_2$, which might have increased exchangeable Ca content of the soil and thus changed the exchangeable Al to insoluble Al(OH)$_3$ form at high pH (Haynes and Ludecke, 1981). The effects observed on exchangeable Al is in agreement with the findings of Crawford and Su (2008) who reported a reduction of exchangeable Al and Aluminium saturation to adequate levels following the application of lime in acidic soil. Similar lime by P interaction effects on exchangeable Aluminium was also observed by Haynes and Ludecke (1981) and Oluwatoyinbo et al. (2005).

Exchangeable calcium, magnesium, and available micronutrients of the soil as influenced by liming and P application

Exchangeable calcium (Ca)

Exchangeable calcium content of the soil was significantly (P ≤ 0.05) affected by the increased lime and P rates. The exchangeable Ca content of the soil increased with increasing rates of lime from 8.45 cmo(+)kg^{-1} (in control treatment) to 22.44 cmol(+)kg^{-1} at the rate of 24373 mg CaCO$_3$ kg^{-1} soil (Table 4). Such considerable increment in the amount of exchangeable

Ca due to liming could be attributed to the precipitation of free Al ions and the deprotonation of the Al-hydroxyl groups by the added base (Ca) and the subsequent increase in the negative charges in the soil exchange complex that retain nutrient cations (Gillman, 1984; Brown and Stecker, 2003).

The difference in the Ca content was also significant between P treated and untreated pots, although significant differences were not obtained between 300 and 600 and 900 mg P kg^{-1} soil treated pots (Table 4). The maximum exchangeable Ca value of 17.48 cmol kg^{-1} was obtained from the application of 1600 mg kg^{-1} soil. This result is in line with that of Haynes and Ludecke (1981) where an increment in exchangeable Ca with increasing P rates was also found. The increase in exchangeable Ca content of the soil as the rate of applied P increase was due to the addition of Ca along with the source of applied P, Ca(H$_2$PO$_4$)$_2$ indicating that P application in the form of Ca(H$_2$PO$_4$)$_2$ can neutralize the Al saturation in the soil by releasing Ca.

Exchangeable magnesium (Mg)

The exchangeable content of the soil showed a non-significant (P ≤ 0.05) difference between the treatments.

This might be due to the type of lime used which is Calcitic limestone which mostly contains calcium carbonate (CaCO$_3$) and because Mg is a poor competitor with Ca for exchange sites, it is often deficient in the topsoil because of the application of large quantities of soluble Ca. Thus, liming to near neutrality with calcic lime in acid soils low in available Mg can exacerbate Mg deficiency (Kamprath and Foy, 1971).

Available micronutrients

The contents of available micronutrients (Fe, Mn, Zn, and Cu) were significantly (P≤0.05) affected only by lime addition, whereas the main effect of P treatments, as well

Table 4. Effect of lime and phosphorus on Calcium and Magnesium content (cmolkg^{-1}) of the soil after harvest.

Treatment		Ca	Mg
	0	8.452^e	2.430
	6093	12.026^d	2.418
Lime rate	12186	17.072^c	2.571
	18280	19.761^b	2.611
	24373	22.441^a	2.607
LSD (0.05)		1.548	NS
	0	13.997^c	2.429
	300	15.534^b	2.529
P rate	600	16.620^{ab}	2.605
	900	16.118^{ab}	2.527
	1600	17.483^a	2.546
LSD (0.05)		1.548	NS
CV (%)		12.54	9.65

*Main effect means within a column or row followed by the same letter(s) are not significantly different at P≤0.05, NS = Not significant.

Table 5. Effects of lime and P rates on available micronutrients (Fe, Mn Zn, and Cu) in the soil.

Treatment (mg kg^{-1})	Micronutrients (mg kg^{-1})			
	Fe	Mn	Cu	Zn
Phosphorus				
0	27.41	48.52	1.82	0.58
300	27.56	48.60	1.83	0.58
600	27.11	48.49	1.83	0.57
900	27.25	48.45	1.82	0.58
1600	27.16	48.54	1.83	0.58
LSD (5%)	NS	NS	NS	NS
SEM (±)	0.43	2.20	0.041	0.03
Lime				
0	34.66^a	68.89^a	1.63^d	0.67^a
6093	31.21^b	55.92^b	1.75^c	0.63^b
12186	24.71^c	47.62^c	1.86^b	0.59^c
18280	23.19^d	35.26^d	1.93^a	0.51^d
24373	22.72^d	34.92^d	1.96^a	0.48^d
LSD (5%)	0.54	2.79	0.051	0.032
SEM (±)	0.431	2.20	0.041	0.03

*Main effect means within a column followed by the same letter are not significantly different from each other at P≤0.05; NS = Non-significant.

as the interaction effects of lime and P fertilizer applications on the contents of all the four micronutrients, were not significant (P>0.05) (Table 5).

The available Fe, Mn, and Zn contents of the soil were markedly reduced, while the contents of available Cu were increased as the lime rates increased from 0 to 24373 mg CaCO$_3$ kg^{-1} soil (Table 5). The highest average available Fe (34.66 mg/kg), Mn (68.89 mg/kg), and available Zn (0.67 mg kg^{-1}) were recorded under the lime-untreated plots, while the lowest 22.72, 34.92, and 0.48 mg kg^{-1} of Fe, Mn, and Zn, respectively, were observed in the pots with the highest rate of lime application. Contrary to available Fe, Mn, and Zn, the highest (1.96 mg kg^{-1}) and lowest (1.63 mg kg^{-1}) available Cu were obtained at

Table 6. Effect of lime and phosphorus on dry matter yield (g) of barley on the soils

Treatments (mg kg^{-1} soil)		Phosphorus					Lime mean
		0	300	600	900	1600	
	0	17.49	24.12	27.33	29.02	29.30	25.45[b]
	6093	18.33	24.74	28.15	29.36	30.86	26.29[b]
Lime	12186	20.59	27.47	28.95	31.52	32.13	28.13[a]
	18280	21.06	28.80	29.80	32.22	32.79	28.93[a]
	24373	22.06	28.75	30.02	32.24	32.43	29.10[a]
P mean		19.908[d]	26.777[c]	28.85[b]	30.87[a]	31.50[a]	
LSD(0.05)				0.930			
CV (%)				4.60			

*Main effect means within a column followed by the same letter(s) are not significantly different at P≤0.05.

the highest and lowest (zero) rates of lime treated pots, respectively (Table 5).

The reduction in the concentrations of Fe, Mn, and Zn with increasing rates of liming could be attributed to the reduction of their solubility with liming, as was also reported by Havlin et al. (1999). These authors indicated that the addition of adequate lime reduces the solution concentration of many micronutrients particularly Fe and Mn and soil pH values in the range of 5.6 to 6.0 are usually sufficient to minimize toxicity while maintaining adequate availability of micronutrients. The results of the present study are also in agreement with Somani (1996) who found that as the rate of lime applied to acid soils increased, plant-available Fe, Mn, Zn, and B contents of soil decreased, whereas Mo and Cu increased. Another author Adane (2014) reported a decreased available micronutrients such as Fe, Mn, Zn and increments of available Cu with lime addition.

Barley dry matter yield and phosphorus concentration in the tissue of barley as influenced by increasing levels of lime and P

Dry matter yield

The dry matter yield (DMY) of barley was significantly (P ≤ 0.05) increased by the increasing rates of P and lime applications, while the interaction effect did not have a significant effect on dry matter yield (Table 7). All of the applied levels of lime resulted in significantly increased DMY of barley compared to the DMY yield obtained under the control treatment (Table 6). The highest DMY (29.10 g) was observed with a lime rate of 24373 mg CaCO$_3$ kg^{-1} soil, although this was not significantly different from the DMY (28.130 and 28.935 g) obtained from the application of 12186 and 18280 mg CaCO$_3$ kg^{-1} soil, respectively. This is in line with the findings of Dolling et al. (1991) which indicated that lower rates of lime were found to increase the top and root DMY of barley as compared to higher lime rates.

The dry matter yield of barley also increased with increasing P addition (Table 6). The highest (31.5 g) DMY was noted at the rate of 1600 mg P kg^{-1} soil and the lowest (19.91 g) in the control treatment. According to FAO (1984), annual crops require P predominantly in the early stage of growth. The observed DMY increase with increasing rates of P fertilizer might be due to the high P demand of barley at the establishment stage and the low available P content of the soil as was also reported by Caddel et al. (2004) and Mahler (1983). Moreover, Anetor and Akinrinde (2006) pointed out that with high rates of P fertilizer additions, the soil sorption sites are satisfied and P level increases to sufficiency level for crop production in acid soils.

Phosphorus concentration in barley tissue

Barley tissue P concentration was significantly affected by the interaction effects of lime and P. Phosphorus concentration in the barley tissue increased with increasing levels of lime and phosphorus (Table 7). The highest P content 5.47 µg g^{-1} was recorded with the application of 24373 mg lime kg^{-1} soil and 1600 mg P kg^{-1} and the lowest was recorded in the control pots. The increased barley tissue P due to liming and P application could be due to the improved uptake and utilization of soil and fertilizer P as a result of liming (Haynes and Ludecke, 1981; Ukrainetz, 1984; Desta, 1987). Amelioration of Al toxicity by liming characteristically results in greatly increased P uptake by plants, even when the availability of soil P may remain unchanged or even decreased (Haynes, 1982).

Effect of lime and P on phosphorus fixation

Iron and aluminium-P

High rates of fixation before planting (155 mg^{-1} kg) and after harvest (132 mg^{-1} kg) were observed at the highest

Table 7. Effect of lime and phosphorus on barley tissue phosphorus content ($\mu g\ g^{-1}$)

Treatments (mg kg^{-1} soil)		Phosphorus					Lime mean
		0	300	600	900	1600	
Lime	0	1.22^m	2.25^j	2.75^i	3.57^g	3.78^{fg}	2.72
	6093	1.69^l	2.63^i	3.04^h	3.69^{fg}	3.85^f	2.98
	12186	1.97^k	3.20^h	3.85^f	4.59^d	5.21^b	3.77
	18280	2.02^{jk}	3.23^h	4.12^e	4.85^c	5.47^a	3.94
	24373	2.05^{jk}	3.65^{fg}	4.36^{de}	4.90^c	5.22^{ab}	4.04
P mean		1.79	2.99	3.63	4.32	4.71	
LSD (0.05)				0.116			
CV (%)				4.57			

*Main effect means within a column followed by the same letter(s) are not significantly different at P≤0.05.

Table 8. Status Fe-Al-P before planting and after harvest.

Treatments	Fe-Al-P (mg/kg) before planting	Fe-Al-P (mg/kg) after harvest
Control	57.50	30.00
Optimum lime applied(12186 mg kg^{-1})	38.00	32.50
High rate of phosphorus (1600 mg kg^{-1})	155.00	132.00
Low rate of phosphorus (300 mg kg^{-1})	62.00	53.00
Optimum lime + low rate of P (12186 mg kg^{-1}+ 300 mg kg^{-1})	61.50	47.50
Optimum lime + high rate of P (12186 mg kg^{-1} + 1600 mg kg^{-1})	122.50	110.00

Table 9. Status of Ca-P before planting and after harvest.

Treatments	Ca-P (mg/kg) before planting	Ca-P (mg/kg) after harvest
Control	1.30	1.00
Optimum lime applied (12186 mg kg^{-1})	2.50	2.00
High rate of phosphorus (1600 mg kg^{-1})	2.00	1.00
Low rate of phosphorus (300 mg kg^{-1})	2.00	1.00
Optimum lime + low rate of P (12186 mg kg^{-1}+ 300 mg kg^{-1})	2.00	2.00
Optimum lime + high rate of P (12186 mg kg^{-1}+ 1600 mg kg^{-1})	3.00	3.00

rate of phosphorus application, whereas the lowest Fe-Al-P was observed in optimum lime treated pots (Table 8). This might be due to the high amount of P available for fixation at the highest rate of P application. This result is similar to that of Banik and Mukhyopadhayay (1986), which showed the sum of Al-P and Fe-P fractions increased with time, but the amount of increase was higher in superphosphate than rock phosphate treated soils. The values of all treatments were higher before planting than their respective values after harvest (Table 8). This might be due to the release of some fixed P during the growing season that will be taken up by plants (Sharma et al., 1980).

Calcium bound P

The highest rate of P fixation by Ca (2.5 mg kg^{-1}) before planting was observed at the optimum rate of lime and highest rate of P, whereas the lowest Ca-P (1.3 mg kg^{-1}) was recorded in control pots (Table 9). This might be due to the increment of Ca in soil both from lime and phosphorus fertilizer. Therefore, Ca-P was higher in pots treated with both lime and P than those treated with P or lime alone. This result is in line with that of Piccolo and Huluka (1985) who found increases of Ca-P with CaCO$_3$ content.

The results showed that phosphorus was dominantly

fixed by iron and aluminium in all treatments as compared to fixation by Ca (Tables 8 and 9). This might be attributed to the low pH of the soil (Sharma et al., 1980) whereby phosphorus was dominantly fixed by iron and aluminium. This result is in agreement with the findings of Alemayehu et al. (2017) who reported that the Al + Fe-associated P was the dominant inorganic P pool. The low content of Ca-P and high content of Al- Fe-P observed in the present study confirmed that the soil was at an advanced stage of weathering (Puranik et al., 1979).

Conclusion

The results showed that the selected soil chemical properties (except Mg) and plant parameters (Barley tissue P concentration and dry matter yield) were significantly ($P \leq 0.05$) influenced by the applied rates of lime and/or P fertilizer. The soil pH was markedly increased by lime addition and thus the toxic effect of soil acidity was reduced and nutrient availability and barley growth were improved. The highest lime rate increased pH from 4.66 to a maximum of 6.15 and reduced exchangeable Al drastically from 1.31 to 0.00 cmol(+) kg^{-1}. The addition of P also resulted in a significant reduction in exchangeable acidity and Al, although it did not significantly affect the soil pH. The lime treatment that increased soil pH to 6.15 also resulted in increased barley DMY.

The result of this study indicated that adjusting soil acidity by applying 18280 mg kg^{-1} lime (CaCO$_3$) could be optimum for almost all the studied soil chemical parameters such as exchangeable acidity, exchangeable Al, exchangeable Ca, and micronutrients and P concentrations in the plant material and barley dry matter yield. However, since the experiment was conducted only in a greenhouse, repeating the trial in a field as well as at different sites would be important to have insight on the residual effects of lime and P and draw sound recommendation.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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