Evaluation of Lime Requirement Estimation Methods for Acid Soil Management and Yield of Bread Wheat and Food Barley in Wadla District of North Wollo Zone of The Amhara Region

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Abstract

Soil acidity is a major challenge constraining agricultural productivity in the highlands of Ethiopia while liming is the most common practice for its mitigation. However, accurate estimation of lime requirement (LR) has been a concern since liming practice began. Thus, field research was carried out at Wadla district of North Wollo Zone of the Amhara Region in 2014 and 2015 to evaluate the accuracy of different lime testing methods in predicting LR and investigating the response of bread wheat and food barley to the combined use of lime and phosphorus (P) fertilizer. The experiment was composed of a factorial combination of four lime testing methods; (SMP single buffer, $Ca(OH)_2$ direct titration, permissible acid saturation percentage (PASP) and exchangeable acidity (EA)) three phosphorus levels (0, 10 and 20 kg P ha^{-1} for bread wheat and 0, 15 and 30 kg P ha^{-1} for food barley). The treatments were laid out in a randomized complete block design with three replications. Calcitic lime was applied by broadcasting three weeks before planting. Significant yield response to the main effect of liming was obtained at the testing site where the soil pH was 5.14 for wheat and 5.0 for barley, while there was no significant yield response to liming where the soil pH varied from 5.25 to 5.60 for wheat and >6.0 for barley. The highest mean wheat grain yield (3.6 t ha^{-1}), and barley, (3.2 t ha^{-1}), were obtained from plots treated with lime estimated by SMP buffer method which is statistically at par with the yield obtained from plots treated with lime estimated by $Ca(OH)_2$ titration method. Similarly, wheat yield was significantly affected by main effect of phosphorus at two testing sites, while barley yield was significantly affected by phosphorus at all sites. The highest wheat grain yield (3.7 t ha^{-1}) was obtained from 20 kg P ha^{-1}, while, the highest barley grain yield (3.25 t ha^{-1}) was obtained from 30 kg P ha^{-1} gave. The lime estimated by SMP buffer $Ca(OH)_2$ titration methods raised the soil pH by 0.3 to 1.4 units. The amount of lime estimated by $Ca(OH)_2$ titration method was lower by 41.7% than LR estimated with SMP buffer method indicating that SMP buffer method tends to overestimate the LR. On the contrary, PASP and EA methods were found to underestimate the LR. Thus, $Ca(OH)_2$ titration method can be recommended for LR estimation among the methods evaluated in this study.

Keywords: *Acidity, lime requirement, lime testing, liming, wheat.*

Introduction

Acid soils are rampant and occupy about 41 percent of the land in Ethiopia (Schlede, 1989; Taye, 2007). Soil acidity problem in the country extends from south-west to north-west limited by the eastern escarpments of the Rift Valley. Out of the 41% of total coverage, 28% are moderate to weakly acidic (pH of 5.5 - 6.7); 13.2% are strong to moderately acidic (pH < 5.5) and nearly one-third have aluminum toxicity problem (Schlede, 1989). Soil acidification and soil erosion are the major soil degradation issues in the humid and highland areas of North Wollo Zone of the Amhara Region. Different studies have shown that soils in the highland areas of North Wollo including the present study area, Wadla district, have become acidic ranging from moderately to slightly acidic (Unpublished data).

Acid soils are a problem to agriculture production due to the consequences of nutritional disorders, deficiencies of essential nutrients such as calcium, magnesium, molybdenum, and phosphorus, and toxicity of aluminum, manganese and hydrogen activity (Carver and Ownby, 1995; Jayasundara *et al.*, 1997). Amendments of acid soil by different liming materials can raise soil pH, benefiting soil properties and plant growth and as a result liming is widely practiced for improving the acid soils productivity (Edmeades and Ridley, 2003; Lal, 2006; Omogbohu Anetor and Akinkunmi Akinrinde, 2007). Lime requirement (LR) is the amount of liming material that must be applied to soil to raise its pH to the level selected for near-optimum plant growth (McLean, 1973). Thus, to reclaim the soil acidity problems in North Wollo Zone, the North Wollo Zone Bureau of Agriculture with Dessie Regional Soil Testing Laboratory conducted soil er, the LR testing method i.e., permissible acid saturation percentage method (PASP) as described by Taye *et. al.* (2007 unpublished), which had been formerly used to determine LR was reported to underestimate the actual LR. Some soil testing laboratories in the region have later adopted SMP single buffer method (Shoemaker *et al.*, 1961) for LR determination.

However, different LR testing methods can give widely divergent results (Peech *et al.*, 1965). Certain methods are better suited to specific soil conditions depending on the physico-chemical characteristics and buffering capacity of the soil (Mehlich *et al.*, 1976). Many qualitative and quantitative methods have been used to estimate the LR including $CaCO_3$ incubations, titration techniques, buffer methods, determination of exchangeable aluminum, and indirect LR determination methods. Lime requirement estimation with buffer methods such as SMP buffer method and Adams and Evans buffer methods (Adams and Evans, 1962), are indirect lime estimation methods developed in US for American soils based on calibration/regression experiments with the widely accepted LR determination method i.e., soil incubation with $CaCO_3/Ca(OH)_2$ (Mehlich *et al.*, 1976; Barrow and Cox, 1990). Therefore, these indirect LR determination methods need to be calibrated and validated to the Ethiopian soils before they are directly adopted. In addition, the level of accuracy of any LR testing methods needs to be tested and validated under field conditions.

On top of that, highly weathered tropical and acid soils have strong P sorption capacities which intensify the limitation of land suitability. Phosphorus (P) fixation by the predominant Al^{3+} and Fe^{2+} ions in strong acid soil conditions leads to P deficiency. Therefore, the lime application needs to be integrated with P fertilizer supply in order to achieve maximum crop yields in acid soils. This study was, therefore, proposed with the objectives of selecting the most appropriate and relatively accurate LR determination methods suitable for the study area and similar agro-ecologies, and evaluating the yield response of wheat and barley crops to the combined application of lime and P fertilizer.

Materials and Methods

Site description

The study was conducted in 2014 and 2015 main cropping seasons in Wadla district of North Wollo zone of the Amhara Region. The study district is situated with an altitude range of 2000-2800 meters above sea level and within the geographical coordinates of 11^{o} ^{o} all of 800-1200 mm with minimum and maximum temperature of 17 and $22^{o}C$, respectively.

Experimental procedures

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Soil samples were collected from ten farmers' fields prior to starting the experiment for pH analysis (1:2.5 soil:water ratio). According to the ratings by Jones Jr (2002), seven famers fields with surface soil pH ranging from strongly to slightly acidic were purposively selected for the study. Four LR estimation methods including 1) SMP single buffer method (Shoemaker *et al.*, 1961), 2) $Ca(OH)_2$ direct titration method (Liu *et al.*, 2004), 3) permissible acid saturation percentage method-PASP (Taye *et. al.,* 2007 unpublished) and 4) exchangeable acidity method (EA) multiplied by a correction factor of 1.5 (included in the second experimental year) were used as LR estimation methods.

Description and soil testing procedures of the LR estimation methods

SMP-single buffer (SB) method

10 ml of SMP buffer (pH 7.5) was prepared and added to the soil-water slurry (1:1 Soil:Water suspension) which was used for pH determination. The soil-buffer mixture was closed tightly and shaken with a mechanical shaker at 250 excursions per min for 10 minutes. The mixture was then left to settle for 20 minutes. The pH of the soil-buffer mixture was measured to the nearest 0.01 pH unit by inserting the pH electrode into the solution of the soil-buffer mixture while swirling. Finally, the LR to the target soil pH of 6.5 was obtained from the final soil-buffer pH measured and existing reference calibrated data developed in the US.

$Ca(OH)_2$ direct titration method

30 ml distilled water was added to 30 g of air dried and ground soil sample which passed through a 2 mm sieve. The soil water mixture (1:1 Soil:Water ratio) was thoroughly and continuously mixed with a glass rod for 30 minutes and left to settle down for 30 min. The initial soil pH was measured by inserting a pH electrode (calibrated with the standard procedure) in the soil-water solution while swirling. Since titration curves are nearly linear within the pH range of most agricultural surface soils (4.5 to 6.5), three aliquots of ($Ca(OH)_2$) were used to develop the slopes of the titration curves for each soil. Three aliquots of 3 ml of 0.022M $Ca(OH)_2$ solution were added to the above soil-water mixture with 30 minutes interval while mixing thoroughly for 30 min after each addition of the 3 ml aliquot of 0.022M $Ca(OH)_2$ solution. The change/raise in the soil pH was measured by inserting the pH electrode in the soil solution while swirling.

The titration curve was plotted by taking the pH values (4 pH values including the initial pH measurement) measured against an equivalent amount of $CaCO_3$ (kg ha^{-1}) to the volume of 0.022M $Ca(OH_{)2}$ added (Eq. 1). A linear regression graph was fitted by plotting the amount of lime in the abscissa and the change in soil pH measured in the ordinate. The LR was calculated based on the slopes of the linear regression equations and the pH difference between initial pH (y-intercept) and the desired pH i.e 6.5 as shown in the equation below (Eq. 2);

$CaCO_3$ (1000 kg ha^{-1}) = V x 0.146, where V (ml) is the volume of 0.022M $Ca(OH)_2$
Eq. 1

$$\text{LR (kg CaCO3 per ha)} = \frac{6.5 - Intercept}{Slope}$$

Permissible acid saturation percentage method (PASP)

$$\text{LR (kg CaCO3 per ha)} = 1160x\left[Exchangeable\ acidity - \frac{1}{10}(ECEC)\right].$$

Where, 1/10 (ECEC) is meant for the assumption that the permissible acid saturation percentage level for wheat and barley is 10% (1/10).

Exchangeable acidity method (EA)

$$LR, CaCO_3\ (kg/ha) = \frac{cmolEA/kg\ of\ soil * 0.15\,m * 10^4\ m^2 * B.D.(Mg/m^3) * 1000}{2000} * 1.5.$$

Where, a 1.5 multiplication factor was adopted based on a recommendation by Iticha *et al.* (2016).

Liming, fertilizer applications and planting

In the field evaluation study, the LRs determined using four lime testing methods and control (without lime) were factorially combined with three levels of P fertilizer (0, half and full of the recommended P, i.e 20 and 30 kg P ha^{-1} for wheat and barley, respectively). The treatments were arranged in a randomized complete block design with three replications. Agricultural calcitic lime, produced from Dejen lime factory, with moisture content of 1.06%, fineness factor of 0.52 and calcium carbonate equivalence (CCE) of > 90% according to Asrat *et al.* (2014) was broadcast evenly and incorporated in to the plow layer (20 cm) of the study fields three weeks before planting. Phosphorus fertilizer was applied in a band all at planting, while, N (69 and 46 kg N ha^{-1} for wheat and barley, respectively) was applied in a row half at planting and the remaining half at tillering (40 days after planting).

The size of each experimental plot was 12 m^2 (3 m * 4 m) with a spacing of 1 m between experimental plots and replications. Bread wheat variety - *Sora* and food barley variety - *Agegnehu* were used for the study. The crops were planted by drilling in a row with 20 cm spacing and at a seeding rate of 150 and 120 kg ha^{-1} for wheat and barley, respectively. There were 20 rows of plants in each plot out of which the innermost 18 rows were harvested and used for data collection and analysis.

Soil sampling and analysis

Composite surface (0-

application of lime for analysis of pH (H_2O and 0.01 M $CaCl_2$), texture, exchangeable acidity, exchangeable Al^{3+}, available P, exchangeable Ca, Mg, K, and Na. Surface (0-20 cm) soil samples were also collected after harvesting from each plot for analysis of soil pH, exchangeable acidity and exchangeable Al^{3+}. The soil analysis was done following the standard soil testing procedure as described by Sertsu and Bekele (2000).

Data collection and analysis

Grain yield was measured at maturity from the innermost 18 rows and was adjusted to a 12.5% moisture content. Fresh biomass weight was measured by weighing the fresh total above ground biomass of the harvested rows. While, the dry biomass weight was measured by taking a straw sample with the seed spikes, drying in an oven at 105 ^{o}C for 12 hours and adjusting the fresh biomass weight into dry basis by using the moisture content measured after an oven dry. Plant height was measured at maturity from random five plant samples of the harvestable rows, from ground level to the tip of the spike including the awns. Thousand seed weight was also measured by weighing 1000 seeds on a sensitive balance. All the relevant agronomic and soil data recorded were subjected to analysis of variance (GLM procedure) using SAS software version 9.00 (SAS Institute, 2004). The LSD mean separation method at 5% probability level was used to separate treatment means.

Results and Discussion

Status of soil physico-chemical properties before liming

Selected soil physico-chemical properties of soils (0-20 cm) of the seven experimental fields in the two experimental years are shown in the Tables below (Table 1 - 4). Soil acidity levels of the experimental fields were ranging from pH 4.97 to 6.00, which fall in the range of very strongly to moderately acidic, based on the ratings by Jones Jr (2002).

Table 1. Some physico-chemical properties of wheat experimental fields in 2014

Testing			Exch. H^+	Exch. Al^{3+}	Exch. acidity	
Site	pH (H_2O)	pH ($CaCl_2$)	meq/100 g soil			Acid Sat (%)
Site 1	5.14	4.43	0.380	0.65	1.024	12.70
Site 2	5.51	4.63	0.128	-	0.128	2.10

	Exch. Ca+Mg	Exch. Na	Exch. K	ECEC	Sand	Silt	Clay	
Testing	Exch. Ca+Mg	Exch. Na	Exch. K	ECEC	Sand	Silt	Clay	Textural
Site	meq/100 g soil				%			class
Site 5	7.50	0.195	0.205	9.5321	16	40	44	Silt clay
Site 6	5.05	0.087	0.397	5.6296	22	50	28	Clay loam
Testing								Textural
Site	meq/100 g soil				%			class
Site 1	6.55	0.195	0.269	8.0381	24	48	28	Clay loam
Site 2	5.55	0.130	0.256	6.0642	26	48	26	Clay

Table 2. Some physico-chemical properties of wheat experimental fields in 2015

Testing site	pH (H_2O)	Exch. acidity (meq/100 g soil)	Organic Carbon (%)	Available P (mg kg^{-1})	Textural class
Site 3	5.25	0.192	1.78-1.98	2.90-3.22	Sandy clay loam
Site 4	5.60	0.120	3.17-3.37	2.42-3.02	<<

Table 3. Some physico-chemical properties of barley experimental fields in 2014

Testing			Exch. H^+	Exch. Al^{3+}	Exch. acidity	
Site	pH (H_2O)	pH ($CaCl_2$)	meq/100 g soil			Acid Sat (%)
Site 5	4.97	4.50	0.580	1.06	1.632	17.1
Site 6	6.00	4.75	0.096	-	0.096	1.70

Table 4. Some physico-chemical properties of barley experimental field in 2015

Testing site	pH (H_2O)	Exch. acidity (meq/100 g soil)	Organic Carbon (%)	Available P (mg kg^{-1})	Textural class
Site 7	4.70	0.576	2.38-2.57	4.84-6.76	Sandy clay loam

LR estimated based on the four testing methods

The LR predictions for the experimental fields based on the three (first year) and four (second year) LR testing methods such as SMP buffer method, $Ca(OH)_2$ direct titration method, PASP method and EA method (added in the second experimental year) are shown in the Tables below (Tables 5 and 6).

Table 5. LR ($CaCO_3$ t ha^{-1}) of wheat experimental fields based on the four LR testing methods

Testing sites	SMP buffer	$Ca(OH)_2$ titration	PASP	Exchangeable acidity	Experimental year
Site 1	13.4	8.8	0.3	-	2014
Site 2	9.9	5.0	NL	-	2014
Site 3	3.3	2.22	NL	0.32	2015
Site 4	1.2	1.26	NL	0.20	2015
Mean	6.95	4.32	-	0.26	

NL: No lime is required based on prediction of the method

Table 6. LR ($CaCO_3$ t ha^{-1}) of barley experimental fields based on the four LR testing methods

Testing sites	SMP buffer	$Ca(OH)_2$ titration	PASP	Exchangeable acidity	Experimental year
Site 5	15.1	9.30	0.8	-	2014
Site 6	9.0	4.20	NL	-	2014
Site 7	4.0	2.17	-	0.97	2015
Mean	9.4	5.2	-	-	

NL: No lime is required based on prediction of the method

Effect of application of lime and P fertilizer on the yield of wheat

The first-year result indicated that the main effects of the application of lime rates determined with three different LR estimation methods had significant ($P<0.05$) effect on the yield of wheat at site 1 (Table 7). However, the yield of wheat at site 1 was not significantly affected by application of P fertilizer, which might be due to the better soil fertility status of the soil as this testing site was close to a homestead and there is a possibility of manure and kitchen waste addition. The yield response to the application of lime at site 1 was most likely attributable to raise in the soil pH and elimination of exchangeable Al^{3+} toxicity as the level of Al^{3+} was reduced from 0.65 meq/100 g to 0 meq/100 following liming. This result is supported by Lamond and David (1995), Okalebo *et al.* (2002) and Osundwa *et al.* (2013) who reported that application of lime significantly improved the productivity of wheat on acidic soils. Similarly, Kettering *et al.* (2005) reported that the increase in the agronomic yields due to liming might be attributed to the increases in soil pH, reduction in the ion toxicity of H or Mn and reduction in nutrient deficiency (Ca, P, or Mo) as well as due to the indirect effect of better physical condition of the soil. At testing site 2, there was a significant yield response to the application of P fertilizer (Table 7), which might be accounted for the low soil fertility status and P limitations to crop growth in the study district (FAO, 1986). However, the yield of wheat was not significantly (P>0.05) affected by the application of lime at site 2. This might be due to the less adverse effect of the soil acidity level (pH 5.51) of the site on the yield of wheat as wheat is reported to be tolerant to the pH level of 5.2 (Mahler and McDole, 1987).

Table 7. Main effects of application of lime rates ($CaCO_3$ t ha^{-1}) and P fertilizer rates (P kg ha^{-1}) on the yields of wheat (kg ha^{-1}) at site 1 and 2 and pooled over sites in 2014

Lime Rates*	Site 1		Lime Rates*	Site 2		Combined	
	Grain yield	Total biomass		Grain yield	Total biomass	Grain yield	Total biomass
Control (0)	3596.2b	9279.8b	0	3872.9	10014.2	3734.6bc	9647.0ab
SMP (13.4)	4252.5a	10821.8a	9.8	4063.7	9791.7	4158.1a	10306.7a
$CaOH_2$ (8.8)	4002.2a	10763.9a	5.0	3877.9	9572.6		

This might be accounted for the less adverse effect of the soil acidity level of the testing sites on the growth of wheat as the surface soil pH levels of the testing sites were in the range of 5.25 to 5.60 (Table 2). However, the main effect of P was found to significantly affect the yield of wheat at site 3, while, at testing site 4 the yield of wheat was not significantly affected by P which might likely be due to the effect of other growth limiting conditions as it can be seen from the very low yield recorded from this site. The pooled analysis of variance over the two testing sites showed that both the main effect of liming and P had a significant effect on the grain yield of wheat. However, there was no significant yield difference among the lime rates applied with the three LR estimation methods (Table 8). Lime by site interaction effect on the grain and total biomass yield was not significant, while, P by site interaction effect was significant indicating the variation in the yield response of wheat to P across the testing sites in the second year.

Table 8. Main effects of application of lime rates ($CaCO_3$ t ha^{-1}) and P fertilizer rates (P kg ha^{-1}) on the yields of wheat (kg ha^{-1}) at site 3 and 4 and pooled over sites in 2015

Lime Rates*	Site 3		Lime Rates*	Site 4		Combined	
	Grain yield	Total biomass		Grain yield	Total biomass	Grain yield	Total biomass
Control (0)	3902.9	9196.4	0.00	1700.0	3817.9	2875.2b	6686.4
SMP (3.30)	3881.4	9302.6	1.20	2188.5	4464.7	3140.7ab	7186.0
$CaOH_2$ (2.22)	4318.7	9590.0	1.26	2020.7	3807.7	3237.3a	6506.1
Exch. acid. (0.32)	4138.9	9392.3	0.20	2008.6	4092.6	3206.9a	6919.1
LSD (5%)	ns	ns	LSD	ns	ns	285.3	ns
P rates*			P rates*				
Control (0)	3823.9b	8687.7b	0	2125.8	4212.9	3015.3b	6450.3
10	3976.3b	9474.3a	10	1796.5	3889.6	2985.5b	6682.0
20	4374.6a	9828.5a	20	2025.2	4007.0	3367.7a	7333.6
LSD (5%)	400.1	568.8	LSD	NS	NS	246.9	NS
CV (%)	9.8	6.6	CV (%)	17.1	14.3	12.8	10.3

**Treatment means followed by the same letter are no significantly different at p> 0.05. ns: Non-significant at p>0.05.*

The pooled analysis of variance of the agronomic data collected overall testing sites and experimental years revealed that the grain yield of wheat was affected by the main effects of both lime and P fertilizer (Table 9). The highest grain and dry biomass yields were obtained from the lime rate determined by SMP buffer method being statistically at par with the grain yield obtained from lime rate determined by $Ca(OH)_2$ titration method. However, the average lime rate (4.32 t ha^{-1} $CaCO_3$) estimated with $Ca(OH)_2$ titration method was lower by 37.6% than the average lime rate (6.93 t ha^{-1} $CaCO_3$) estimated with SMP buffer method. Similarly, the highest grain and total biomass yields were obtained from the application of 20 kg P ha^{-1} followed by the yields from the application of 10 kg P ha^{-1} (Table 9).

Table 9. Main effect of lime rates ($CaCO_3$ t ha^{-1}) and P fertilizer rates (kg P ha^{-1}) on the yields of wheat pooled over testing sites and experimental years

Lime rates*	Grain yield (kg ha^{-1})	Total biomass (kg ha^{-1})
Control (0)	3343.9b	8301.3
SMP buffer (6.93)	3679.3a	8746.4
$CaOH_2$ titration (4.32)	3633.9a	8433.0
LSD (5%)	202.7	Ns
P rates*		
0	3413.3b	8019.0b
10	3503.4b	8524.9a
20	3742.6a	8917.6a
LSD (5%)	202.7	445.6
CV (%)	11.7	10.5

*Treatment means followed by the same letter are no significantly different at p> 0.05. ns: Non-significant at p>0.05.

Effect of application of lime and P fertilizer on the yield of barley

The grain and dry biomass yield at site 5 and 7, where the soil pHs were strongly acidic, were significantly (P<0.01) affected by the main effects of liming (Table 10). The main effect of the application of P was found to significantly (P<0.01) affect both grain and straw yields at all testing sites. However, there was no significant (P>0.05) interaction effect of liming and P fertilizer on the yield of barley at all testing sites. The significant response to liming might be due to the subsequent rise in the soil pH of the study sites after liming. Haynes (1984) and Kettering *et al.* (2005) also reported that the increase in the agronomic yields of barley due to liming is attributed to the improvement in soil pH, reduction in the ion toxicity of H^+, Al^{3+} or Mn^{2+}, release and availability of nutrients like Ca, P, or Mo as well as due to indirect effect of better physical condition of the soil. The positive effect of liming on the growth and grain yield of barley on acid soils was reported by a number of authors (Tang *et al.*, 2003; Kovacevic *et al.*, 2006). Ito *et al.* (2009) also confirmed the positive responses of barley root growth and yield improvements on acidic Andosols due to liming.

The significant yield response to the main effect of applied P fertilizer might also be attributed to the low soil fertility of the testing sites and the supply of P in the P treated plots as compared to the none P treated plots where indigenous soil P was most likely fixed in unavailable form due to the very strong soil acidity. However, at the testing site 6, the yield was not significantly ($P>0.05$) affected by the application of lime (Table 10). This might be due to the slight soil acidity level (pH 6.0) of the testing site which as a result had no significant adverse effect on the yield of barley. But barley yield was rather affected significantly by the main effect of the application of P which was due to the low soil fertility characteristics of the study district (World Bank, 1983; FAO, 1986).

At those testing sites where the soil acidity was very strongly acidic, the highest mean grain and dry biomass yields were recorded from the application of lime estimated with SMP buffer method followed by the mean grain and dry biomass yields obtained from the application of lime determined with $Ca(OH)_2$ titration method. The highest grain and dry biomass yield at all testing sites were recorded from the application of 30 kg P ha^{-1} which was statistically at par with the yields obtained from 15 kg P ha^{-1}. At the testing site 6, where the soil pH was slightly acidic (pH 6.0), the mean grain and dry biomass yields obtained were about 100% higher than the mean grain and dry biomass yields obtained at testing site 5, where the soil was very strongly acidic (pH 4.97), in the same experimental year (2014). This indicated the effect of strong soil acidity on the yield of barley though lime was added as the effect of liming on soil acidity is slow and gradual. This result is supported by Farhoodi and Coventry (2008) who reported a substantial yield increment of barley, wheat, and faba bean a year after lime application.

Likewise, the pooled analysis over the three testing sites in the two experimental years revealed significant ($P<0.01$) response of barley yields to the main effects of lime and P fertilizer (Table 11). The highest mean grain and dry biomass yields of 2.8 and 7.9 t ha^{-1}, respectively, were obtained from application of lime estimated with $Ca(OH)_2$ titration method being statistically at par with the grain and dry biomass yields of 2.7 and 7.8 t ha^{-1}, respectively, obtained from lime estimated by SMP buffer method. Application of lime estimated with $Ca(OH)_2$ titration and SMP buffer methods increased the grain yield of barley by an average of 15.5 and 19.1%, respectively as compared to the non-limed treatment. Similarly, application of 30 kg P ha^{-1} gave the highest grain yield which was statistically at par with the grain yield obtained from 15 kg P ha^{-1}. Grain yield advantages of 37.7 and 26.8% over the treatment where P was not applied were also obtained from the application of 30 and 15 kg P ha^{-1}, respectively.

Table 10. Mean barley grain and dry biomass yields (kg ha^{-1}) affected by the main effects of liming and P fertilizer at three testing sites in 2014 and 2015

	2014					2015		
	Site 5			Site 6			Site 7	
Lime rates* (CaCO$_3$ t ha^{-1})	Grain yield	Dry biomass	Lime rates (CaCO$_3$ t ha^{-1})	Grain yield	Dry biomass	Lime rates (CaCO$_3$ t ha^{-1})	Grain yield	Dry biomass
Control (0)	1229.8c	4045.3c	0.0	2976.8	7689.9b	0.0	2429.9c	7860.1c
SMP buffer (15.1)	2054.9a	6401.2a	9.0	3235.0	8111.1a	4.00	3193.7a	9835.4a
Ca(OH)$_2$ titration (9.3)	1655.8b	5446.5b	4.2	3314.5	8332.2a	2.17	2941.0ab	9218.1ab
PASP (0.8)	952.7c	3671.2c	0.0	-	-	Exc. Acidity - EA (0.97)	2803.3bc	8847.7b
Mean	1512.4	4936.8	Mean	3175.5	8044.4	Mean	2841.9	8940.3
CV (%)	18.0	13.4	CV (%)	12.4	5.0	CV (%)	13.7	10.5
LSD (5%)	290.34	684.12	LSD (5%)	ns	379.5	LSD (5%)	381.8	913.9
P rates* (kg P ha^{-1})			P rates (kg P ha^{-1})			P rates (kg P ha^{-1})		
Control (0)	1011.9c	3838.2b	0	2811.5 b	7435.2b	0	2378.0b	8101.9b
Half of rec. (15)	1645.4b	5356.9a	15	3337.5a	8261.8a	15	2991.6a	9058.6a
Full rec. (30)	1916.6a	5615.4a	30	3377.4a	8436.2a	30	3156.4a	9660.5a
Mean	1512.4	4936.8	GM	3175.5	8044.4	Mean	2841.9	8940.3
CV (%)	18.0	13.4	CV (%)	12.4	5.0	CV (%)	13.7	10.5
LSD (5%)	248.27	591.69	LSD (5%)	393.2	379.5	LSD (5%)	330.7	791.5

**Treatments followed by the same letter are not significantly different at 0.05 probability level; ns=non-significan*

Table 11. Mean barley grain and dry biomass yields (kg ha^{-1}combined over years affected by the main effects of lime rates and P fertilizer

Lime rate* ($CaCO_3$ t ha^{-1})	Grain yield	Dry biomass yield
Control (0)	2346.7b	6887.4b
SMP buffer (9.37)	2709.0a	7786.6a
$Ca(OH)_2$ titration (5.22)	2794.5a	7993.7a
Mean	2630.2	7579.9
CV (%)	13.0	11.2
LSD (5%)	197.7	483.5
P rates* (kg P ha^{-1})		
Control (0)	2162.3c	6742.7b
Half of rec. (15)	2741.3b	7785.7a
Full rec. (30)	2977.8a	8169.5a
Mean	2630.2	7579.9
CV (%)	13.0	11.2
LSD (5%)	197.1	482.3
Lime rate*P rates*Site	ns	ns

**Treatments followed by the same letter are not significantly different at 0.05 probability level; ns=non-significant; Lime rates = the mean lime rate estimated with the two methods of the three testing sites.*

Effect of application of lime estimated with different lime testing methods on soil acidity

The result of laboratory analysis for the soil samples collected at harvesting from the seven experimental fields of both test crops in the two experimental years showed that LR estimated with SMP buffer and $Ca(OH)_2$ titration methods raised the soil pH significantly to the level optimum for wheat and barley growth (Table 12 and 13). However, the application of LR determined with PASP and exchangeable acidity (EA) methods were not found to significantly raise the soil pH as compared to the pH measured from the control treatment. Thus, PASP and EA methods were found to underestimate the actual LR.

The exchangeable acidity and exchangeable Al^{3+} analyzed from the soil samples collected at harvesting was zero due to the significant rise in the soil pH >5.5 as a result of liming. The increase in the soil pH measured at harvesting from the control treatment as compared to the pH measured before planting might be due to the dynamic property of soil pH which was raised as a result of the dry season period during harvesting (Olojugba and Fatubarin, 2015). In addition, although the lime was broadcast with much care to the lime-treated plots, there was a possibility of movement of dust of lime to the control plots by wind due to its fineness. This might also lead to an increase in soil pH on the control plots measured at harvesting.

The rise in the surface soil pHs measured at harvesting due to the application of LRs determined with SMP buffer and $Ca(OH)_2$ titration methods were statistically similar. However, the average amount of lime rate determined with $Ca(OH)_2$ titration method was lower by 37.6 and 44.7% than the lime rate determined by SMP buffer method from wheat and barley experimental fields, respectively. This result is supported by Liu *et al.* (2004) who found out that the 3-points prediction from the direct titration with 30 minute interval time between additions of 0.022M $Ca(OH)_2$ estimated approximately 80% of the soil acidity and LR determined by the widely accepted standard procedure for lime determination i.e., 3-day incubation of the soils with $Ca(OH)_2$. On the contrary, Liu *et al.* (2004) also reported that titration of 1:1 soil:0.01 M $CaCl_2$ solution mixture with $Ca(OH)_2$ was more accurate than titrating soil:water mixture. According to McLean *et al.* (1978), titration of acidic soils with $Ca(OH)_2$ in l:5 soil:water suspensions (though the titration method differs from the method used in this study) yielded LRs that were similar to those obtained by the standard incubation with $CaCO_3$ to pH 6.5 over a 20 months period.

Table 12. Effect of application of lime ($CaCO_3$ t ha^{-1}) on soil pH (at harvesting) from four wheat experimental fields

2014					2015				
Site 1		Site 2		pH	Site 3		Site 4		pH
Lime rate*	pH	Lime rate	pH	Combined	Lime rate*	pH	Lime rate	pH	Combined
Control (0)	5.81b	0.0	6.20b	6.00b	Control (0)	5.75b	0.00	5.79	5.77b
SMP (13.4)	6.49a	9.8	6.93a	6.71a	EA (0.32)	5.97ab	0.20	5.81	5.89ab
CAOH (8.8)	6.63a	8.0	6.74a	6.69a	SMP (3.30)	6.19a	1.20	5.98	6.08a
PASP (0.3)	5.97b	-	-	5.97b	CAOH (2.22)	6.10ab	1.26	5.87	5.98ab
LSD (5%)	0.32	LSD (5%)	0.24	0.22	LSD (5%)	0.39	LSD (5%)	ns	0.22
CV (%)	5.21	CV (%)	3.67	4.55	CV (%)	6.57	CV (%)	4.02	5.43

**Treatment means followed by the same letter are no significantly different at p> 0.05. SMP: SMP buffer method; CAOH: $Ca(OH)_2$ titration method; PASP: Permissible acid saturation percentage method; EA: Exchangeable acidity method.*

Table 13. Effect of application of lime ($CaCO_3$ t ha^{-1}) on soil pH (at harvesting) from three barley experimental fields

2014					2015	
Site 5		Site 6		pH	Site 7	
Lime rate*	pH	Lime rate	pH	Combined	Lime rate*	pH
Control (0)	5.6b	0.0	6.2b	5.9c	Control (0)	5.62b
SMP (15.1)	6.7a	9.0	6.8a	6.8a	EA (0.97)	5.86ab
CAOH (9.3)	6.5a	4.2	6.5ab	6.5a	SMP (4.0)	6.21a
PASP (0.8)	5.4b	0.0	-	5.4b	CAOH (2.17)	6.16
LSD (5%)	0.38	LSD (5%)	0.43	0.30	LSD (5%)	0.35
CV (%)	6.4	CV (%)	6.7	6.4	CV (%)	5.82

*Treatment means followed by the same letter are no significantly different at p> 0.05. SMP: SMP buffer method; CAOH: $Ca(OH)_2$ titration method; PASP: Permissible acid saturation percentage method; EA: Exchangeable acidity method.

Conclusion and Recommendation

The study result revealed that different lime testing methods generate different LR to raise the soil pH level to the desired level. The 3-point $Ca(OH)_2$ direct titration and SMP single buffer methods were found to effectively increase the soil pH level to the desired pH level (pH 6.5). However, PASP and EA methods were found to underestimate the LR. The lime amount estimated by $Ca(OH)_2$ titration method was on average lower by 37.6% for wheat plots and by 44.7% for barley plots than the amount estimated by SMP buffer method indicating SMP buffer method tends to overestimate the LR. Thus, $Ca(OH)_2$ titration method was found to be the most appropriate and accurate lime estimation method among the methods evaluated in this study. Though $Ca(OH)_2$ titration method was found to consume more time as compared to SMP buffer method, it could be recommended as the best LR determination method for routine use in soil testing laboratories as it can reduce about 38-45% of the cost of extra lime expenses predicted by SMP buffer method.

As the buffer methods such as SMP buffer methods are rapid methods of lime testing for routine use in soil testing laboratories, developing conversion factor based on the current recommendation i.e $Ca(OH)_2$ titration method is recommended to accelerate the soil testing process while maintaining the accuracy level. Moreover, we suggest further study on $Ca(OH)_2$ 1-point and 2-point titration evaluations on soil:0.01 M $CaCl_2$ mixture instead of 3-point soil:water mixture to shortening the time required for the soil testing. Although this study simultaneously verified the accuracy of the LRs predicted based on different lime testing methods on the field, calibration of the lime testing methods with the standard soil incubation procedures with $CaCO_3$ or $Ca(OH)_2$ is also recommended.

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