EVALUATION OF LIME REQUIREMENT METHODS FOR ACIDIC SOIL: A CASE STUDY FROM NEDJO DISTRICT, WEST WOLLEGA ZONE, ETHIOPIA

M.Sc. THESIS

BY

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JULY 2020

JIMMA, ETHIOPIA

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Submitted to Jimma University College of Agriculture and Veterinary Medicine, School of Graduate Studies, in Partial Fulfillment of the Requirements for the Degree of Master of Science in Soil Science

July 2020

Jimma, Ethiopia

DEDICATION

I dedicate this thesis to my parents who have sown the interest of learning in my mind and wishing me a great career throughout my life.

STATEMENT OF THE AUTHOR

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BIOGRAPHICAL SKETCH

The author, Abraham Tadesse, was born in September 1986 G.C. at Lembuda Kebele, Lemo District, Hadiya Zone of the Southern Nation Nationalities Regional State. He attended his Elementary Education at Masbira and Alemu Woldehana Elementary School from 1994 - 2001 in Hosanna town and his Secondary School at Yekatit 67/25 Senior Secondary High School from 2002-2003. Later, the author attended his Preparatory School at Wachamo Preparatory School from 2004-2005. After the successful completion of Ethiopian Higher Education Entrance Qualification Certificate Examination (EHEEQCE) in 2005, he joined Hawassa University in 2006 and graduated in 2008 with a Bachelor of Science in Applied Chemistry. Then, since May 2009 he had served in the Ministry of Peace, Addis Ababa being an equitable development advisor for the Emerging Regions. Finally, in September 2018, he joined the Postgraduate Program of Jimma University in order to pursue his MSc study in soil science.

ACKNOWLEDGEMENTS

LIST OF ACRONYMS

CEC	Cation Exchange Capacity
LR	Lime Requirement
SMP-SB	Shoemaker, McLean and Pratt Single Buffer
SMP-DB	Shoemaker, McLean and Pratt Double-Buffer
ASP	Acid Saturation Percentage
PBS	Percentage of Base Saturation
NWADO	NEDJO Woreda Agricultural Development Office
ENMANS	Ethiopia National Meteorological Agency; NEDJO station
pHB	Buffer pH
NPS	Nitrogen Phosphorus Sulphur
Av. P	Available Phosphorous
OC	Organic Carbon
OM	Organic Matter
RMSE	Root mean square error

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EVALUATION OF LIME REQUIREMENT METHODS FOR ACIDIC SOIL: A CASE STUDY FROM NEDJO DISTRICT, WEST WOLLEGA ZONE, ETHIOPIA.

ABSTRACT

Soil acidity is the most serious challenges to agricultural production and productivity worldwide in general, and developing countries in particular. Liming is a common agricultural practice worldwide, which is used for increasing the productivity of acidic soils. Liming reduces aluminum toxicity, increases the soil pH up to values where the availability of Al decreases; and the bioavailability of essential nutrients, such as phosphorous is enhanced. In this study, three buffer methods for determining the lime requirements, namely, the Shoemaker - McLean - Pratt single buffer (SMP-SB); Shoemaker - McLean - Pratt double buffer (SMP-DB) and new Woodruff buffer methods were evaluated. These buffer methods were evaluated using $Ca(OH)_2$-titration to a pH of 6.5; and $CaCO_3$-incubation to a pH of 6.0 and 5.5 as a reference pH because they are reliable and were often used as a calibration for buffer methods. In this study a total of 24 soil samples representing the major agricultural acid soils in Nedjo district were considered. The lime requirement needed for adjusting the pH to 6.5, 6.0 and 5.5 were correlated with the amounts of exchangeable aluminum (r = 0.80), exchangeable acidity (r = 0.82), Organic carbon (r= -70) and soil pH (r= -0.97). The study revealed that the SMP-DB is the best method for determining the lime requirement for the Nedjo district acid soils. The SMP-DB method gave the highest correlation coefficient values (r=0.98) with the reference pH, the least variations from the ideal lines. The sensitivity of the SMP-DB method was comparable for soils of high (>5.88 t/ha) and low (<5.88 t/ha) lime requirements, while the sensitivity of SMP-SB and New Woodruff methods were poor for soils of low and high lime requirements. Pot experiment in lath-house the highest plant height, spike length and biomass were obtained at pH 5.99 and 6.14 in Vertic Luvisols and Rhodic Nitisols, respectively; while the biomass yield of wheat was declining at pH levels beyond these. Since it might not be necessary to lime these soils to pH levels higher than 6.0. Hence, to ameliorate the soil over there, the SMP-DB method is recommended.

Key Words: Soil Acidity; Al toxicity; Exchangeable Acidity; Lime requirement; Buffer Method and Nedjo.

1. INTRODUCTION

Soil acidity is a complex of several factors involving plant nutrient deficiencies and toxicities, low activities of beneficial microorganisms, and reduced plant root growth which limits absorption of nutrients and water (Fageria and Baligar, 2008). It is the most serious challenges to agricultural production and productivity worldwide in general, and developing countries in particular. At global level, areas affected by soil acidity (pH < 5.5) is estimated at 4 billion hectares, representing about 30% of the total ice-free land area of the world (Sumner and Noble, 2003). From 3.01 billion ha in Africa, 658 million ha of land (22%) is acidic soil (Sumner and Noble, 2003). Most of these acidic soils are found in tropical and subtropical African countries such as Tanzania, Kenya, Uganda, Ethiopia, etc. In Ethiopia 43% of the total arable land is affected by soil acidity (Behailu, 2015).

According to Mesfin (2007) soil acidity was expanding in scope and magnitude across different regions in Ethiopia and it became a serious threat to crop production in the western, southern, northwestern and central highlands. This is attributed to higher precipitation, which exceeds evapotranspiration that subsequently leaches appreciable amounts of exchangeable bases from the soil surface resulting in most soils having a pH range of 4.5–5.5, low organic matter content (< 20 g/kg) and low available plant nutrients (Temesgen *et al.,* 2011). Abdenna *et al.,* (2007) also reported that the acidity problem in East and West Wollega Zone of Oromia Region was critical. In Western Wollega Zones, the large proportion of exchangeable acidity was due to exchangeable Al^{3+}. According to Hirpa *et al.* (2013), decrease in pH leads to increase in net charge (low in CEC) which leads to lose of soil fertility and ultimately reduces land productivity in Nedjo district.

Soil acidity has negative impact on nutrient availability and causes Al and Mn toxicity (Osundwa *et al.,* 2013). Furthermore, soil acidity can cause rapid deterioration in soil physicochemical properties such as soil organic carbon (SOC), cation exchange capacity (CEC), soil structure, porosity and texture. Acidification has effect on complexation of metals with organic matter, dispersion of colloids and eventual bioavailability and trace elements (Bolan *et al.,* 2003).

Maintaining the pH of the soil is important because it ensures conditions conducive to plant growth, including adequate base saturation of the cation exchange capacity (CEC), reduction in the concentration (toxicity) of micronutrients such as aluminum and manganese, and an increase in the availability of plant nutrients and microbial activity (Anetor and Ezekiel, 2006).

Soil acidity problems are commonly corrected by applying lime. Surface liming ameliorates topsoil acidity in a relatively short term, but is generally slow in ameliorating subsoil acidity. Amelioration of soil acidity by surface liming to attain a pH range which is suitable for better crop production is crucial in order to get reasonable yields in acid prone areas. Hence, lime is the major means of ameliorating soil acidity (Anetor and Ezekiel, 2006), because of its very strong acid neutralizing capacity, which can effectively remove existing acid, stimulate biological activity and reduce toxicity of heavy metals.

Methods based on pH or exchangeable Al or acidity (Al^{3+} and H^{+}) are incapable of accurately estimating the acidity hazard across textural classes, especially if there are marked differences across soils in terms of their physical and chemical properties. Soil pH measurement only gives the concentration of dissociated hydrogen (H^{+}) ions in solution, which is a very small fraction of the total acidity present. From this point of view, it is clear that determination of lime requirement (LR) based on exchangeable acidity only leads us to unrealistic rate of lime to reclaim soil acidity (Farina *et al.,* 1991). Therefore, LR should be determined based on soil's pH and its buffering capacity, which is determined by clay and the amount of OM (Aitken *et al.,* 1990).

Of the various methods developed to determine the potential acidity and consequently the LR of soils, buffer pH methods have been used because of their simplicity and rapidity. The buffer methods used in this thesis include: Shoemaker-McLean-Pratt Single buffer (SMP-SB), Shoemaker-McLean-Pratt Single buffer (SMP-DB) and New Woodruff buffer methods, and $Ca(OH)_2$ - titration and $CaCO_3$ - incubation as reference methods. Incubation in the field and titration in the laboratory would be ideal for determining LR, but it is prohibitive due to the high cost and time required. Instead, the $CaCO_3$ moist-incubation and $Ca(OH)_2$-titiration methods have been considered as a standard for comparative purposes by some scientists (McLean *et. al.,* 1966; Kamprath, 1970; Mehlich, 1976). Several laboratories use different

methods even though no better method has been preferred for the rate of lime that fit for amendment of the acid soils. Therefore, selection of method of lime requirement that would be accurate, rapid and better suited for routine soil analyses have been a pressing issue for acid soils management. In line with the above facts, this research activity was carried out to evaluate different lime requirement determination methods for amendment of acidic soils in the Nedjo district acid soils.

Although studying soil acidity problems and lime requirement estimation methods have been done in some part of the country, quantitative analysis using soil laboratory tests to acquire appropriate solution for the problem was very little. There needs to be a sound basis for determining the correct amount of lime to apply because soils differ in their initial pH, Al saturation levels and pH buffer capacities. This is particularly more critical in highly weathered soils in which there can be a serious detrimental effect from over and under-liming. For the study area a recommended site specific method to determine lime requirement is not yet available. Thus, the purpose of this study was to recommend the appropriate LR estimation method by comparing three different buffer methods for the study area. Therefore, the objectives of this study were:

General objective:

✓
    To evaluate lime requirement methods for acidic soil in Nedjo district, West Wollega Zone, Ethiopia.

Specific objectives:-

✓
    To study the effects of soil properties on lime requirements of acid soils.

✓
    To develop a suitable methods for determining lime requirements of acid soils in Nedjo district.

✓
    To evaluate the effectiveness of an estimated methods on wheat crop in pot experiment.

Hypothesis:

➢
    The lime requirements determination of acid soils is affected by soil buffer equilibration and soil chemical properties.

2. LITERATURE REVIEW

2.1. Soil Acidity and Its Effects on Soil Properties and Crop Production

Acidity refers to concentration of hydrogen cations in a soil solution (FAO, 2006). The natural pH of a soil depends on the nature of the material from which it was developed (TSO, 2010). Increased soil acidity causes solubilization of Al, which is the primary source of toxicity to plants at pH below 5.5, and deficiencies of P, Ca, Mg, Mo, N, K and micronutrients (Kariuki *et al.,* 2007; Mesfin, 2007). Theoretically, soil acidity is quantified on the basis of hydrogen (H^+) and aluminium (Al^{3+}) concentrations of soils and affects the nutrients availability (Yihenew, 2002).

Due to differences in chemical composition of parent materials, soils will become acidic after different lengths of time. Thus, soils that developed from granite material are likely to be more acidic than soils developed from calcareous shale or limestone (Johnson, 2002). Soil nutrient depletion due to erosion and leaching of basic cations from the agro ecosystem is also a very wide spread crop production constraint in Ethiopia (Taye, 2001). Studies conducted by (Dawit et al., 2002), also reported that, due to acidic nature of the soil, most of the soils of the highlands of Ethiopia are deficient in their inherent total available P contents.

For crop production, however, soil acidity is a complex of numerous factors involving nutrient/element deficiencies and toxicities, low activities of beneficial microorganisms, and reduced plant root growth which limits absorption of nutrients and water (Fageria and Baligar, 2008). However, Al^{3+} toxicity is one of the major limiting factors for crop production on acid soils by inhibiting root cell division and elongation, reducing water and nutrient uptake (Wang *et al.,*2006), poor nodulation or mycorrhizal infections (Kochian *et al.,*2004; Delhaize *et al.,*2007), consequently leading to poor plant growth and yield of crops. Soil acidity can decrease crop yield, seedling emergence and survival, establishment, legume nodulation and root growth (Marschner, 2011).

Nanthi and Mike (2003) who reported that although, soil acidity is naturally occurring phenomena, agricultural practices such as the removal of plant residues carrying organic anions and excess cations from the farm or paddock are likely to accelerate soil acidification.

Nair and Chamuah (1993) reported that the concentration of the H^+ to cause acidity is pronounced at pH value below 4, while excess concentration of Al^{3+} is observed at pH below 5.5. On most acid soils, there are several limiting factors for plant growth, including toxic levels of aluminum, manganese, and iron, as well as deficiencies of some essential elements, such as phosphorus, nitrogen, potassium, calcium, magnesium, and some micronutrients (Kochian *et al.,* 2004).

Among these constraints, Al toxicity and P deficiency are the most important once, due to their ubiquitous existence and overwhelming impact on plant growth (Kochian *et al.,* 2004). According to Yihenew (2002) at Injibra area who observed that pH is highly significant ($p<0.01$) and positively correlated with exchangeable bases whereas high significant and negatively correlated with exchangeable acidity.

2.2. Distribution of Acid Soils in Ethiopia

The total area of Ethiopia is 111.8 million hectare out of these only 79 million of hectare is suitable for agriculture, which strong to weak acid soil accounts 43% (Bahilu, 2015). Soil acidity is a severe problem in high rainfall areas of Ethiopia, and can lead to decline or complete failure of crop production (Abdenna *et al.,* 2007). The most strongly acidic soils are found in Western, South western parts of Ethiopia, the central highlands and the high rainfall areas of North western part of the country. The extent of acidity is believed to increase year to year, due to anthropogenic activity and no in-depth studies were made on the causes and extent of acidity. As a result, its exact extent is difficult to ascertain, but available information indicates that, the Western and Southern parts of Ethiopia are dominantly covered by soils with pH < 5.5 (Mesfin, 2007).

In moving from central (West Shewa) to western Ethiopia and South Western Ethiopia including West wollega, the degree of soil acidification that is measured in terms of acid saturation percentage is increased (ASP>60%).

The acidity problem in East and West Wollega zone of Oromia region is critical, and the large proportions exchangeable acidity in these areas was due to exchangeable Al^{3+}, while at West Shewa zone it was due to exchangeable H^+ (Abdenna *et al.,* 2007). As a case in point, a site specific study of soils around Assossa and Wollega revealed that in aggregate, some 67% of soils had pH values less than 5.5 and were very strongly to strongly acidic (Mesfin, 2007). Nevertheless, moderately acidic soils (pH 5.5- 6.5) are distributed through much of the rest of the country (Taye, 2008).

Many findings (Abreha *et al.,* 2012) show that decreasing of the soil pH (increasing acidity) in western and southern Ethiopia was due to intensive rainfalls that can leaches soluble nutrients such as calcium and magnesium and with subsequent replacement by aluminum and hydrogen ions. As reported by Achalu *et al.,* (2012) in western Ethiopia Alfisols, increasing of soil acidity and appearance of exchangeable Al under the cultivated lands showed that intensive cultivation and continuous use of acid forming inorganic fertilizers on acid soils aggravates soil acidity. Likewise, exchangeable bases readily decreased showing declining of basic cations from the exchange complex of the soil colloids (Jaiyeoba, 2003).

2.3. Managing of Acid Soils Using Liming

Both strongly alkaline and strongly acid conditions are generally detrimental to plant life (Haynes and Naidu, 1998; Rengel, 2011). Liming is a major and effective practice to overcome soil acidity constraints and improve crop production on acid soils (Fageria and Baligar, 2008). Soil pH, base saturation, and Al saturation are important acidity indices that are used as a basis for determination of lime rates for reducing crop constraints on acid soils. Besides, crop responses to lime rate are vital tools for making liming recommendations for crops grown on acid soils (Fageria and Baligar, 2008; Rengel, 2011).

The modern agriculture production requires the implementation of efficient, sustainable, and environmentally sound management practices (Fageria and Baligar, 2008). In this context, liming is an important practice to achieve optimum yields of all crops grown on acid soils. Liming materials are used to neutralize soil acidity as liming is the most widely used long-term method of soil acidity amelioration as its success is well documented (Scott *et al.,* 2001; Kaitibie *et al.,* 2002). The rise in pH of soil is associated with the presence of basic cations (Ca^{2+}) and anions (CO_3^{-2}) in lime that are able to exchange H^+ from exchange sites to form

H_2O and CO_2. Ca^{2+} occupies the space left behind by H^+ or Al^{3+} on the exchange site leading to the rise in pH (Fageria *et al.,* 2007; Mesfin, 2007).

Application of lime at an appropriate rate brings several chemical and biological benefits in the soils, which are helpful in improving crop yields on acid soils. Adequate liming eliminates soil acidity via reducing the toxicity of Al, Mn, and H. In addition, liming; improves the soil structure; improves the availability of P; N_2 fixation; and reduces the availability of Mn, Zn and Cu. Efficiency of lime Application is, however, affected by factors, such as quality of the liming material, soil texture, soil organic carbon, crop species and the use of organic manure (Fageria and Baligar, 2008).

According to Rasnake *et al.* (2002), an agricultural liming material, or "Aglime," is a material containing calcium (Ca) and/or magnesium (Mg) compounds capable of neutralizing soil acidity. Soil acidity management by Asmare *et al.* (2015), at northern highlands of Ethiopia, identified application of lime ($CaCO_3$) at the rate of 11.2 ton ha^{-1} increased soil pH from 4.89 to 6.03 and reduced exchangeable Al from 1.28 to 0.07 Cmolc-kg^{-1} soils, respectively. Temasgen *et al*. (2017) also reported that liming at the rate of 2.2 t ha^{-1} improved the P availability by 77.6 % as compared to no liming.

Anetor and Akinrinde (2007) reported that un-limed soil remained acidic (pH 4.8), but liming raised pH (6.1-6.6), and resulted in maximum P release (15.1-17.3 mg kg^{-1}) compared to un-limed soil (4.2-7.1 mg kg^{-1}). Agegnehu *et al.* (2006) also indicated that the application of lime at the rates of 1, 3 and 5 t ha^{-1} consistently increased soil pH from 4.37 to 5.91 as the lime rate increased. Conversely, the exchangeable acidity was significantly reduced from 1.32 to 0.12 Cmolckg^{-1} soils.

2.4. Effects of Lime on Selected Properties of Acid Soils

2.4.1. Soil reactions (pH)

Soil reaction is one of the most important chemical characteristics of the soil solution. Soil reaction is expressed in terms of pH indicating whether the soil is acidic, alkaline or neutral. Soil pH measures the molar activity (concentration) of hydrogen ions in the soil solution. It is a negative logarithmic scale, and hence, a decrease of one unit in pH value implies an increase

in the hydrogen ion concentration by tenfold (Moody and Cong, 2008). Soil pH helps to identify the kinds of chemical reactions that are likely taking place in the soil. It affects nutrient availability and toxicity, microbial activity, and root growth. For agricultural purposes, soils with pH values within the range of 5.8 to 7.5 are more trouble free than those with higher or lower values (Bohn *et al.,* 2001). On acid soils, pH is a critical parameter that influences the physiology of the roots (Hissinger *et al.,* 2003), where it is expressed in root alteration including root weight, volume and length.

Correcting soil pH to a suitable value requires the removal of excess hydrogen (H^+) ions produced by various processes in the soil, by applying liming materials, such as agricultural lime (calcium carbonate), dolomite (magnesium carbonate plus calcium carbonate), or other materials containing basic cations capable to replace excess H^+ (Moody and Cong, 2008). Liming raises soil pH, base saturation, and Ca and Mg contents, and reduces aluminum concentration on acid soils (Fageria and Baligar, 2008). In addition, liming can also cause the aluminum (Al) and manganese (Mn) to move from the soil solution back into solid (nontoxic) chemical forms. Most of the soils have a pH range of 4.5 to 5.5, and contain low organic matter (< 20 g kg^{-1}) and low nutrient availability (Temesgen *et al.,* 2017).

Buni (2014) reported that soil pH increased significantly from 5.03 in the plots without lime to 6.72 at the lime rate of 3750 kg $CaCO_3$ ha^{-1}. Temesgen *et al.* (2017) reported that soil pH was increased and Al^{3+} was markedly reduced to a negligible level after two years of liming at Holeta Agricultural Research Center (HARC). According to these authors, liming at the rate of 0.55, 1.1, 1.65 and 2.2 t ha^{-1} increased soil pH by 0.48, 0.71, 0.85 and 1.1 units, and decreased Al^{3+} by 0.88, 1.11, 1.20 and 1.19 Cmolc-kg^{-1} of soils, respectively. Murata *et al.* (2002) also reported that application of lime at the rate of 2 t ha^{-1} significantly increased topsoil pH values from 4.6 to 6.0. Agegnehu *et al.* (2006) also indicated that soil pH consistently increased from 4.37 to 5.91 as lime rate increased. Conversely, the exchangeable acidity was significantly reduced from 1.32 to 0.12 Cmolckg^{-1} because of lime application. Mesfin *et al.* (2014) also reported that lime combined with P fertilizer gave the highest mean value of soil pH (6.3); while phosphorus fertilizer applied alone had the least pH (5.2). The increased soil acidity causes solubilisation of Al, which is the primary source of toxicity to plants at pH below 5.5 (Kariuki, *et al.,* 2007).

2.4.2. Exchangeable acidity

Exchangeable acidity consisted of exchangeable aluminum (Al^{3+}) and Hydrogen (H^+) that might be present in the exchange sites (Bohn *et al.,* 2001). Exchangeable acidity in soils is almost entirely due to Al^{3+} ions (Bohn *et al.,* 2001). This is because only Al^{3+} is a common exchangeable cation in moderately to strongly acidic soils (Bohn *et al.,* 2001). Exchangeable Al normally occurs in significant amounts, only at soil pH values less than 5.5. Furthermore, as the pH is lowered, the concentration of soluble aluminum, which is toxic, increases (Bohn *et al.,* 2001). The poor growth of plants on acid soils has been associated with the concentration of Al in the soil solution. The Al^{3+} cation can be toxic to roots which is one of the major reasons that soil acidity can affect plant growth. In addition to direct toxic effects of soluble Al^{3+} to plants, it replaces the plant nutrient cations such as Ca and Mg, and simultaneously acts as strong adsorber of phosphate (Marschner, 2011). Studies conducted by (Dawit *et al.,* 2002), also reported that, due to acidic nature of the soil, most of the soils of the highlands of Ethiopia are deficient in their inherent total available P contents.

Liming soils to reduce toxic levels of A1 is recognized necessary for optimal crop production on acid soils. Liming resulted in the increase of exchangeable Ca, and thus, in percentage base saturation, with concomitant decreases in levels of exchangeable Al, Fe and Mn (Fageria and Baligar, 2008). When lime is added to acidic soils, the activity of Al^{3+} is reduced by precipitation as $Al(OH)_3$. Applications of lime highly decreased exchangeable acidity and Al^{+3}, as the level of applied lime rates increased. For instant exchangeable acidity decreased from the initial level of 1.32 to 0.1 Cmolc-kg^{-1} when lime was applied at the rate of 2.2 t ha^{-1} (Temasgen *et al.,* 2017). Reports also indicate that exchangeable acidity is a function of soil pH and presence compounds such as $Al(OH)^{3+}$ or $Al(OH)^{2+}$, and weak organic acid ions held at the colloidal surfaces of the soil (Hinrich *et al.,* 2001).

According to Achalu *et al.* (2012), the increased grain yields obtained on soils from all land use types limed with different lime rates when compared to their respective controls are mainly associated with reduction of concentration of exchangeable acidity and enhancement of exchangeable Hirpa *et al.* (2013) reported that application of lime at the rate of 2000mg $CaCO_3$/Kg (9 t ha^{-1} lime), the pH of the soil increased from 4.45 to 5.14, the exchangeable

acidity reduced to 0.39 from 5.19 Cmolc-kg^{-1} soils and acid saturation dropped from 52.7 to below 4.13%, which are optimum for common bean growth in Nedjo districts. Susolski (2004) reported exchangeable Al^{+3} as 2.76 ± 0.17 and total exchangeable acidity as 3.19 ± 0.93 Cmolc-Kg^{-1} soils. So, high exchange between acid cations (Al^{+3} and H^{+}) and basic cations (Na^{+}, K^{+}, Ca^{+2}, and Mg^{+2}) is expected and Al^{+3} toxicity may affect the availability of basic cations especially during plant roots uptake of the nutrients.

2.4.3. Available phosphorus

Total phosphorus (P) gives an indication of the total reserve of the nutrient in the soil and it is a poor indicator of the availability level, since most of the soil P might be fixed (Anetor and Akinrinde, 2006). Fageria and Baligar, (2008) also reported that the application of lime increased the extractable P in the pH range of 5.0-6.5, after, and thereafter, it was decreased in the Brazilian Oxisol, which might be associated with the release of P ions from Al and Fe oxides, which were responsible for P fixation (Fageria and Baligar, 2008).

Bohn *et al.* (2001) reported that soils that are high in exchangeable and soluble Al, liming might increase plant P uptake by decreasing Al, rather than increasing P availability. This might be due to improved root growth where Al toxicity is alleviated, allowing a greater volume of soil to be explored. Temasgen *et al.* (2017) also reported that liming at the rate of 2.2 t ha^{-1} improved P availability by 77.6 % as compared to no liming.

2.5. Response of Crops to Lime Applications

Crop yield responses to liming are closely related to exchangeable-Al reductions. So measurement of exchangeable-Al has also been used as a liming criterion. The amount of Al^{3+} on the permanent soil-exchange sites is largely influenced by soil pH (McLean, 1976). Liming to pH 5.5 ensures elimination of Al^{3+} toxicity. The maximum yield of relatively Al-sensitive crops like alfalfa, soybean, and barley is realized when the exchangeable-Al level is lower than 0.1 Cmolc-kg^{-1} of soils of Al^{3+} (Ragland and Coleman, 1959; Hoyt and Nyborg, 1987).

Achalu *et al.* (2012); and Shiferaw and Fekadu (2014) have reported that barley yield was increased as a result of the increased pH and reduced exchangeable aluminum and in part due

to lime application. Sole application of 3.7 t ha^{-1} limes has also been reported to have increased wheat grain yield by twice of the control treatment (Guangdi *et al.,* 2009).

According to Whalen *et al.* (2002), wheat grain plus straw production were lower in unfertilized soils than in soils that received lime and manure applications, but only the highest lime and manure application rates (4 g $CaCO_3$ kg^{-1} and 40 g manure kg^{-1}) produced more wheat than fertilized soils. Sims (1996) reported that Wheat (*Triticum aestivum* L.) was most productive at a soil pH of 6.0. Caires *et al.* (2006) reported Surface liming caused increases up to 140% in the grain yield of wheat. Accordingly Temesgen *et al.* (2017), reported wheat and productivity improvements from 0.9 t ha^{-1} to 1.6 t ha^{-1} due to lime use only, respectively, from an average application of 2.2 t lime ha^{-1}.

Buri *et al.* (2005) reported that experiment conducted in Nigeria where 2.0 t ha^{-1} and 1 t ha^{-1} lime was applied, and 72% and 48% yield increases was found over no lime treatment, respectively. Application of lime significantly increased root and shoot yields of soybean in Nigeria (Anetor and Akinrinde, 2006), grain yields of soybean in Brazil (Caires *et al.,* 2006). Similarly, Andric *et al.* (2012) reported increased soybean yields by 44% as a result of lime application.

Abraha *et al.* (2013) reported that integrated lime and NP fertilizer application increased biomass by 173% and grain yield by 236% over control at Tsegede highlands of northern Ethiopia. Hence, the research works identified that integrated use of lime with organic and inorganic fertilizers have been paramount effective than the main effects of each input. Jovanovic *et al.* (2006) found that liming considerably influenced the yields of the field crops and single application of high rates was the better choice compared with repeated use of low rates. Similar observations were also reported by Samia (2007) and Basak (2010).

In line with this, several findings (Palm *et al.,* 2001 and Abreha *et al.,* 2012) revealed that low OM content of cultivated soils could be attributed to increased rates of organic matter oxidation, mainly caused by tillage activities; decline in total organic matter inputs; increased soil temperatures due to exposure of the soil surface, increased wetting and drying cycles, and losses by erosion.

2.6. pH Buffering Capacity

The pH buffering capacity of a soil is defined as its resistance to changes in pH when an acid or a base is added. It can be expressed as the quantity of protons required for changing the soil pH one unit (mmol H^+ kg^{-1} soil pH^{-1}) (Rowell, 1994). Magdoff and Weil (2004) found that organic matter is an important determinant of pH buffering in soils. They also reported that soils are very well buffered above pH 7 and below pH 4. Within the pH range of most agricultural soils (4.5 to 6.5) the pH relationship is nearly linear.

Aitken *et al.,* (1990) also found that the buffering capacity of a soil is governed by organic carbon, clay and exchangeable acidity. There was a better relationship between pH buffering capacity and organic carbon than between pH buffering capacity and clay. This is consistent with the large difference in buffer capacities of clay and organic matter. For example, organic matter may have a buffering capacity >300 times that of kaolinite (Weaver *et al.,* 2004).

Machacha (2004) evaluated the ability of several buffer methods including SMP and AE single-buffer solutions to predict the actual LR of acid soils of the eastern region of Botswana to pH 6.5. He found that the buffer capacity, organic carbon, exchangeable acidity, and extractable Al were the most important soil properties influencing LR of acid soils in eastern Botswana. In relation to sub soils in eastern Queensland which are characteristically low in organic matter and high in exchangeable Al, Aitken et al. (1990) reported that exchangeable Al (or exchange acidity) may be of greater importance in determining pH buffer capacity.

2.7. Lime Requirement Determination

The lime requirement (LR) is the amount of limestone ($CaCO_3$) needed to increase the pH of the plow layer of acid soil to a desired level (McLean, 1970). The lime requirement is affected by a soil pH and its buffering capacity, which is determined by soil texture, type of clay minerals, and the amount of organic matter (Johnson, 1979). Many qualitative and quantitative methods have been used to estimate the lime requirement including $CaCO_3$ incubations, titration techniques, buffer methods, determination of exchangeable aluminum, and indirect lime requirement determination methods.

The measured lime requirement must accurately reflect the amount of liming materials need to raise the pH of the soils to the target value when lime is applied under field condition for optimum plant growth and to prevent over liming hazards in soils. Incubation in the field would be ideal for determining LR, but it is prohibitive due to the high cost and time required. Instead, the $CaCO_3$ moist-incubation method has been considered as a standard for comparative purposes by some scientists (McLean, *et. al.,* 1966; Kamprath, 1970; Mehlich, 1976). According to Bache (1988), incubation methods are considered to be reliable but time consuming.

Fox (1980) evaluated the Yuan DB method on 20 Pennsylvania soils. A better correlation was determined when $CaCO_3$ soil incubation (r = 0.967) was used as the reference method than when $Ca(OH)_2$ - titration (r = 0.914) was used as the reference method. Using the $CaCO_3$ soil incubation as a reference method, the Yuan DB method overestimated the LR for soils with a LR <7.44 meq $CaCO_3$ 100 g^{-1} soil and underestimated the LR for soils with a LR >7.44 meq $CaCO_3$ 100 g^{-1} soil.

Tran and van Lierop (1981) worked with 70 Quebec soils and an eight week $CaCO_3$ soil incubation. The Yuan DB method had a high correlation coefficient (r = 0.959) for soils ranging in LR from 1.4 to 40.0 meq $CaCO_3$ 100 g^{-1} soil to pH 6.5. A poorer correlation was found for soils with a LR <10 meq 100 g^{-1} soil (r = 0.877). The Yuan DB method, on the average, predicted 66% of the $CaCO_3$ LR (6.5).

McLean *et al.* (1978) reported the Yuan DB method underestimated the LR for 28 low LR soils (< 4.0 meq 100 g^{-1} soil). The reference method predicted LR was 1.0, 2.0, and 4.0 meq 100 g^{-1} soil versus 0.54, 1.65, and 3.87 meq 100 g^{-1} soil as determined by the Yuan DB method. The Yuan DB method was more accurate for low lime requiring soils than for high lime requiring soils. It predicted 89% and 73% of the LR, respectively for 54 soils from the U.S. McLean *et al.* (1978) also reported that $Ca(OH)_2$ titration to pH 7.2 with 72 hours of intermittent shaking gave values an average of 5% lower than those for $CaCO_3$ incubation to pH 6.8 for 17 months (r = 0.99).

The SMP-SB LR method has been evaluated by numerous researchers. Most of the researchers report that the SMP-SB LR method underestimates the LR for low lime requiring soils (Yuan, 1975; Fox, 1980; Brown and Cisco, 1984). Most of the workers found the SMP-SB LR method to be significantly correlated (r > 0.90) with their respective reference methods (Webber *et al.,* 1977; Loynachan, 1981). The buffer exhibits relatively little buffering capacity from an initial buffer pH of 7.5 down to a pH of 6.9 (McLean, 1978). The vertical change in buffer pH in the pH range of 7.5 to 6.9 would be too great to indicate adequate lime for acid soils very low in cation exchange capacity (McLean *et al.,* 1966).

Ssali and Nuwamanya (1981) reported on two separate experiments, found the SMP-DB method to better predict the mean LR to pH 6.5. For soils with a LR < 4 meq 100 g^{-1} both SMP methods underestimated the predicted LR. The SMP-DB provided a better estimate than the SMP-SB. The second trial used a $CaCO_3$ soil incubation to determine the LR to pH 6.0. This time the two SMP methods both overestimated the predicted LR for soils requiring < 4 meq 100 g^{-1}. The SMP DB provided a better estimate than did the SMP-SB method.

3. MATERIALS AND METHODS

3.1. Description of the Study Site

3.1.1. Location

The study was conducted at Nedjo district West Wollega Zone of Oromia Regional State, Western Ethiopia on acid soils during 2019/20 G.C (Fig. 1). The site is located between 09^0 05' 00" – 09^0 10' 00" N and 35 ^{0} 45' 00" – 35 ^{0} 50' 00" E, which is about 74 km far from Gimbi, the capital town of West Wollega Zone, and 515km from Addis Ababa.
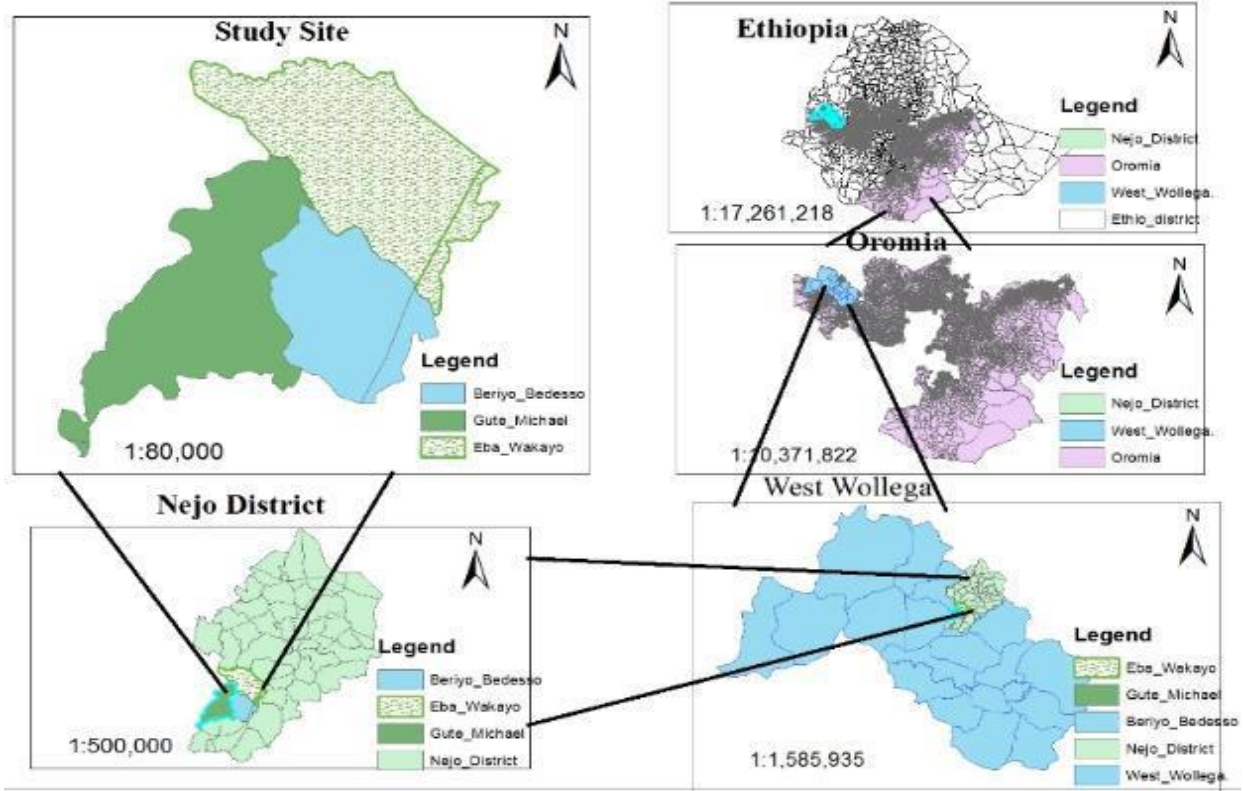
Source: Google maps (2018)

Figure 1: Location map of Nedjo.

3.1.2. Climate

Based on 5 years rainfall and temperature (i.e., 2014-2018) data obtained from Ethiopian National Meteorology Agency, Nedjo Station, the area is characterized by a monomodal rainfall pattern with annual average amount of rainfall ranging from 1600 to 2000 mm. The highest and the lowest rainfalls were received in June and January, respectively. The annual

mean maximum and minimum monthly temperatures were 25.73 and 12.4 ^{0} C, respectively with the hottest month being March followed by February (Fig. 2) (ENMANS, 2019).
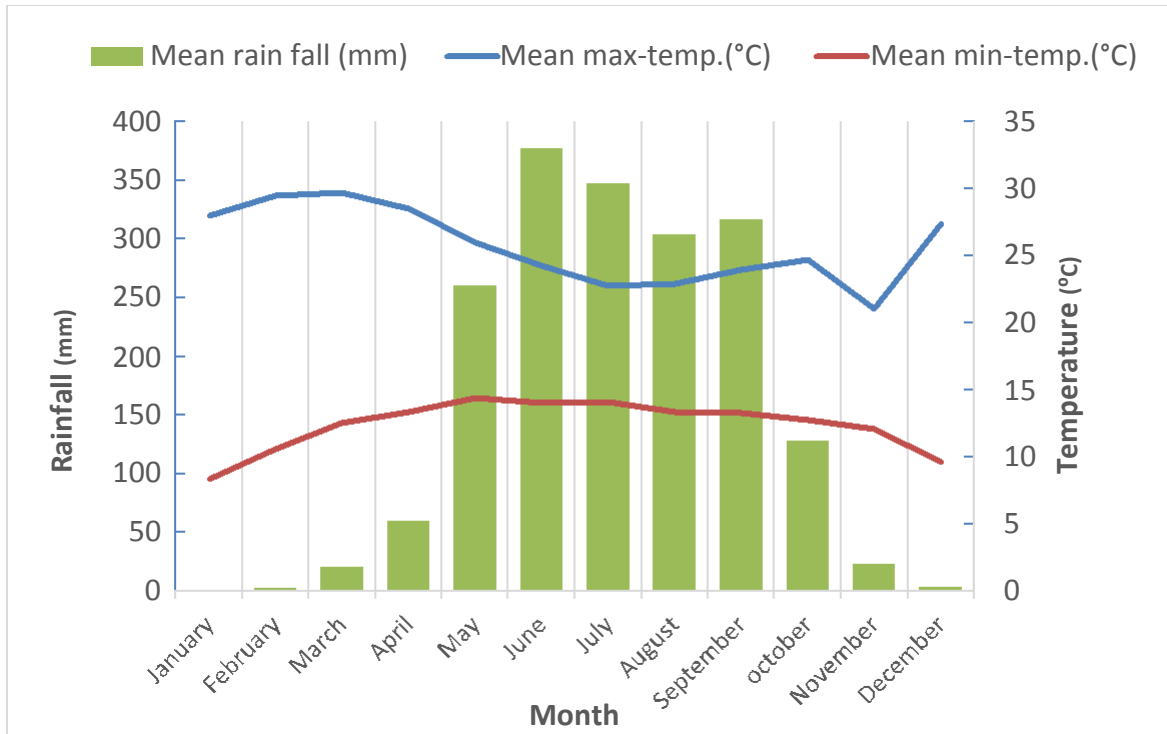
Source: National Meteorological Agency; Nedjo Station (2019).

Figure 2: Mean monthly maximum and minimum temperature (˚C) and mean monthly rainfall (mm) of the experimental area for the year from 2014 - 2018.

3.1.3. Topography and Soil

According to Hirpha *et al.,* (2013) topography of Nedjo District is undulating. The Altitude of the study area ranges between 1600 to 2749 m.a.s.l. The soils of West Wollega Zone are acidic and the degree of acidity varies across districts (Abdenna, 2013). The predominant soil type is Nitisol, which is dark red brown, and characterized by very strong to strongly (mean pH value of soil of Nedjo district is 5.00) (Hirpa *et al.,* 2013).

3.1.4. Land use and socio economy activities

According to the information obtained from the district agricultural development office, the existing land use system is classified as 27.9% rain fed cultivated crops land, 22.3% coffee cultivated land, 16% forest land, 11.1% irrigation cultivated land, 10%bone cultivated land,

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1.2% grazing land, and 11.5% other land. The economic activities of the local society of the study area are primarily mixed farming system that involves animal husbandry and crop production. The major crops of the areas are coffee, maize, sorghum, teff, wheat, barley, sesame, finger millet, haricot bean, faba bean, field pea and lima bean. These major crops are produced usually once in a year by traditional farming system (NWADO, 2019).

3.2. Site Selection Criteria, Soil Sampling and Sample Preparation for Laboratory Analysis

The criteria used to select the 3 kebeles were based on that are rated as high in acidity problem by agricultural bureau and their representativeness of the other kebeles. Field data collection and soil sampling were carried out with the help of topographic map of the study area. At the beginning, a preliminary field observation was carried out using the topographic map and gridded shape-file (scale 1:50,000). Prior to the actual field work, tentative sampling sites were fixed on the gridded shape-file. The undisturbed soil samples of known volume were taken with a sharp-edged steel cylinder forced manually into the soil for bulk density determination at twenty four sites.

Based on the field observation to make one composite sample, 2 to 3 hectares of representative fields were selected for each sample from all 24 sampling sites from three selected kebeles. After demarcation the field, a composite surface soil samples (i.e., 0-20cm) was collected by using auger. The total composite soil samples collected from the study sites were twenty four, and were taken following a zigzag pattern from 24 different sampling points. To make one composite sample 15 to 20 sub-samples were used and were mixed by using plastic sheet. After mixing, approximately 1kg for physicochemical analysis, 10kg for incubation study for each from 24 sampling sites, and 50kg for pot experiment study from 2 sites for each, based on soil types (Rohdic Nitisols, 50kg soil, and Vertic Luvisols, 50kg) with proper labeling on each sampling bag. Finally, each composite sample was air dried ground and passed through 2-mm sieve and placed in a labeled plastic bag for physico-chemical analysis at Jimma Agricultural Research Center Soil Laboratory (JARC) using standard procedures.

3.3. Soils Laboratory Analysis

The soil pH was determined in soil water suspension of 1:2.5 (soil: water ratio) using a pH meter, as described by Van Reeuwijk (1993). Exchangeable acidity (exchangeable H^+ + exchangeable Al^{3+}) was determined through a 30 minute extraction with 1M KCl and titration of the filtrate with 0.05M NaOH using phenolphthalein as indicator (Thomas, 1982). Exchangeable Al^{3+} was estimated by titration with 0.05M HCl after adding 1M KF until pink color of the indicator was disappeared (Thomas, 1982). Exchangeable H^+ was determined by calculating the difference between exchange acidity and exchangeable Al^{3+}.

Particle size distribution (texture) of soils was determined by Hydrometer method (Bouyoucos, 1962). The undisturbed soil samples were used to determine bulk density by core sampler weighing at field moisture content and then dried in an oven at 105 ^{0} C (Baruah *et al.,* 1997) for 72 hours. Organic carbon was determined using the wet digestion method of Walkley and Black (1934) and later on the organic matter content was estimated by multiplying from the organic carbon content by a factor 1.724. Cation exchange capacity (CEC) and exchangeable bases (Ca, Mg, K and Na) were determined using Atomic Absorption Spectrophotometer (AAS) and Flame Photometer after extracting the soil samples by ammonium acetate (NH_4OAc) at pH 7.0 as described by Chapman (1965). Percentage base saturation (PBS) was calculated by dividing the sum of the charge equivalents of the base forming cations (Ca, Mg, Na and K) by the CEC of the soil and multiplying by 100. Available soil P was determined using Bray-II method, as described by Bray and Kurtz, (1945).

3.4. Evaluation of Methods for Determining the Lime Requirement of Acid Soils

3.4.1. Moist $CaCO_3$-incubation study

Out of the twenty-four (24) soil samples the twenty-three (23) soils with an initial pH below 5.5 were selected for incubation studies. The liming material used for this experiment was pure powder $CaCO_3$ which had calcium carbonate equivalence (CCE) 90% which was collected from Jimma Research Center. Eight of 0.5kg samples of each soil were weighed and $CaCO_3$ powder was added at the rate of 0.0, 2.0, 4.0, 6.0, 8.0, 10.0, 12.0 and 14.0 t/ha randomly. After mixing the soil samples with the lime thoroughly, the mixtures were placed in open polythene bags and moistened to field capacity. Additionally, by measuring weight loss of water was added frequently to replace that amount lost via evaporation. The soils were

allowed to be incubated for two months. Finally, after two month the soil samples were air-dried, ground, sieved to pass a 2 mm mesh and stored in closed containers.

The pH of each soil was then measured, and the resulting pH was plotted against the amount of $CaCO_3$ added to the respective soil samples. The amount of $CaCO_3$ in soil required to bring a soil pH to pH 5.5, 6.0 and 6.5 was then determined from the curve. Exchangeable aluminum and exchangeable acidity were also determined by using standard laboratory procedures.

3.4.2. Calcium hydroxide ($Ca(OH)_2$)-titration method

Lime requirements to achieve pH 6.5 in all the 24 soils was determined by $Ca(OH)_2$ - titration. The $Ca(OH)_2$ - titrated values were used as a basis for evaluation of the three buffer methods for determining the lime requirements of acid soils.

Shoemaker *et al.,* (1961) indicated that a 3-day $Ca(OH)_2$ titration to a pH of 7.2 was approximately the same as $CaCO_3$ – incubation to a pH of 6.5 after 20 months. For this reason, lime requirement values obtained by $Ca(OH)_2$ titration method to pH 7.2 was taken as an index of lime requirement's to pH 6.5 in this study, and lime requirement values obtained by buffer methods was also computed on the pH 6.5 basis to allow comparison of the methods.

A total of twenty four soil samples each weighing a gram of soil were mixed with a 20 ml of distilled water on each and then titrated to pH 7.2 with 0.025N $Ca(OH)_2$. After 24 hours, more $Ca(OH)_2$ was added again to bring the pH of soil suspension to pH 7.2. This was repeated over a period of 2 to 3 days until each soil reading remained constant at pH 7.2 for 24 hours. Then the total volume of base used for each sample to maintain pH 7.2 for 24 hours was used to compute the amount of lime in Cmolc-kg^{-1} soil. This amount of lime was then taken as the lime requirement of the soil to pH 6.5.

3.4.3. Buffer methods

In this section, three different buffer methods namely, Shoemaker - McLean - Pratt single buffer (SMP-SB); Shoemaker - McLean - Pratt double buffer (SMP-DB) and New Woodruff buffer methods were evaluated as presented below:

3.4.3.1. Shoemaker - McLean - Pratt single buffer (SMP-SB) method

A 5 g soil sample each was weighed and placed into plastic cups where 5 ml of distilled water was added (Shoemaker *et al.,* 1961). After stirring the soil water suspension, pH was measured using a pH-meter. Then 10 ml of the SMP-SB solution was added to the previous soil-water suspension for those with a soil pH of below 5.54 (Table 1). The soil-buffer suspensions were then shaken continuously for 15 minutes on a mechanical shaker at 175 oscillations per minute. The pH of the soil-buffer suspension was then measured. From the pH readings of the soil-buffer suspension, the amount of lime required to bring a given soil to pH 6.5 and 6.0 were determined from a Table of the Shoemaker *et al*. (1961) (see Appendix 4).

3.4.3.2. Shoemaker - McLean - Pratt double buffer (SMP-DB) method

The buffer mixture was prepared according to Shoemaker *et al.* (1961) and portions of the buffer mixture were adjusted to two pH levels of 7.5 and 6.0 according to (Yuan, 1976) and (McLean *et al.,* 1978).

Two sets of 5 g soil samples were weighed into plastic cups and 5 ml of distilled water was added each. The soil-water suspensions were stirred, and pH determined. Then 10 ml of the buffer mixtures (adjusted to pH 7.5 and 6.0) was added to soil-water suspensions separately. The soil-buffer suspensions were then shaken continuously for 15 minutes on a mechanical shaker at 175 oscillations per minute. Then the pH of the soil-buffer suspensions was measured after 30 minutes standing time. The double-buffer formula [Eq.1] and mathematical function [Eq.2] were used (Yuan, 1974 and 1976). And in the improved SMP buffer method (McLean *et al.,* 1978) was used to convert the soil-buffer pH readings to lime requirement values at pH 6.5, 6.0 and 5.5.

Double-buffer formula: $\underline{\quad}$ $($ $\underline{\quad}$ $\underline{\quad})$ $(\underline{\quad})$ *......... Eq.1*

Where:

- pH1 = Soil-buffer pH in pH 7.5 buffer

- pH2 = Soil-buffer pH in pH 6.0 buffer

- ΔpH1 = 7.5 - pH1

- ΔpH2 = 6.0 - pH2

- Δd°1 / ΔpH1= change in acidity/unit change in pH of 10 ml of pH 7.5 buffer by titration

- Δd°2/ ΔpH2 = change in acidity/unit change in pH of 10 ml of pH 6.0 buffer by titration

- d = the acidity in me/5g of soil measured by the double buffer procedure, and

- x = any chosen pH to which soil is to be limed. In this study x will be 6.5, 6.0 and 5.5.

Mathematical function: -

$$LR \ in \ meq/l00g \ soil = 1.69y - 0.86 \quad \ldots\ldots\ldots\ldots\ldots \quad Eq. \ 2$$

Where: y = 20d.

The mathematical function was used to correct for less than complete reaction with the soil acidity in 15 minutes shaking time and 30 minutes standing time.

3.4.3.3. New Woodruff buffer method.

Calcium acetate and calcium hydroxide were dissolved in 500 mL cool distilled water. Then, salicylic acid was added to acetate-hydroxide solution and the solution mixed vigorously for 2 minutes. Subsequently, after heating a 200 mL distilled water to 70°C, a para-nitrophenol was dissolved in it, which then poured in the previous mixture. Finally, the volume was made to 1000 mL and the pH was adjusted to 7.0±0.05 by HC1 or NaOH.

$$LR \ [Cmolckg^{-1}] = 10 \ (7.0 - pH)\ldots\ldots\ldots\ldots\ldots Eq.3$$

3.5. Pot Experiment to evaluate the effectiveness of estimated methods on wheat crop.

Two soils types (Rhodic Nitosols and Vertic Luvisols) were used in the pot experiment. The pH of the soil was adjusted by adding $CaCO_3$ powder, followed by moist-incubation study for four pH levels of each soil selected. The amounts of $CaCO_3$ required in each soil to achieve any of these pH levels (pH 6.5, 6.0 and 5.5) have been determined based on earlier incubation studies in the laboratory.

Calcium carbonate ($CaCO_3$) was applied to a 2 kg of soil for three pH levels in the pot by broadcasting and mixing thoroughly and uniformly by hand, and let a month before sowing by adding water to moist the soil. Wheat (*Triticum aestivum L.*) was used as test crops. Treatments of acid soils with and without $CaCO_3$ powder were considered in a completely randomized design replicating three times. NPS - Fertilizer at the rate 0.75g was added to each pot. Then ten wheat seeds were sown per pot. All the wheat plants were later thinned to five plants per pot. After 45 days of emergence one of the wheat plants was carefully uprooted for root length measurement. Finally, the data of five wheat plants for plant height at physiological maturity, spike length before threshing and dry matter (biomass and grain yield) after harvesting were collected. For soil analysis the soil pH, exchangeable acidity and exchangeable Al data were collected at last stage.

3.6. Data Analysis and Statistical Procedures

Mean comparisons was made using the least significant difference (LSD) test with $p < 0.05$ and a completely randomized design (CRD) were considered for pot experiment. Correlation was used to determine the strength of relationships among the various soil attributes, lime requirement and related variables. The regression was used to determine the lime requirement methods and soil properties. The root mean square error (RMSE) was used to determine the sensitivity of best lime requirement methods. Correlation and regression analysis were done using Statistical Analysis System (SAS) 9.3 Version statistical software (SAS Institute, 2012). Graphs were generated in Microsoft Excel (Microsoft Corporation, 2010).

4. RESULTS AND DISCUSSION

4.1. Characterization of Soil Physicochemical Properties

The study revealed the textural classes of the soils were clay and clay loam with the clay content ranging from 15 to 57% with mean values of 40.58%. The soil pH ranges from 4.38 to 5.54; exchange acidity varies from 0.22 to 9.36 $Cmolckg^{-1}$ soils; exchangeable aluminum varies 0.16 to 8.75 $Cmolckg^{-1}$ soils; cation exchange capacity (CEC) ranging from 11.54 to 20.30 $Cmolckg^{-1}$ soils; Percentage of base saturation (PBS) ranging from 12.78 to 48.68%; Available phosphorus and organic carbon ranges from 5.60 to 14.75 ppm and 0.44 to 2.15%, respectively (Table 1).

As presented in table 1, the pH of the study area soils was low, and classified as very strongly to strongly acidic (Soil Survey Division Staff, 1993). This result is in line with Mesfin (2007) who reported that the soils around Assosa and Wollega were very strongly to strongly acidic. The low pH value of the soil could be due to the leaching of basic cations such as Ca, Mg, K and Na ions, from the surface soil since the area receives high rainfall. Some of these basic cations could also be removed with above ground biomass harvest since crop residue removal is the common practice at the study area. Nanthi and Mike (2003) who reported that although, soil acidity is naturally occurring phenomena, agricultural practices such as the removal of plant residues carrying organic anions and excess cations from the farm are likely to accelerate soil acidification.

According to, SSSA (1996) the concentration of exchangeable acidity ($Al^{3+} + H^{+}$) and exchangeable Al^{3+} were high (table 1), and this indicates that Al toxicity can be a problem in the area. This is in line with Abdenna *et al.* (2007) who reported that the large proportion of exchangeable acidity in these areas was due to exchangeable Al^{3+}. High soil exchangeable acidity and aluminum might be associated with the occurrence of lower soil pH. The observed low pH value and high value of exchangeable acidity and Al as described by in the similarly could be due to leaching of basic cations and uptake of some basic cations by crops.

Table 1: Some selected characteristics of acid soils in Nedjo district.

Sample codes	PHw (1:2.5)	Ex. Acd	Ex. Al	CEC	Av. P (ppm)	OC	PBS		Texture			
			Cmolckg-1 soil				%	Clay%	Silt%	Sand%	Class
EWP10	4.86	2.46	1.43	15.24	6.80	1.63	22.78	44.00	25.00	31.00	Clay
EWP11	4.91	1.02	0.90	16.55	7.76	1.76	16.77	55.00	24.00	21.00	Clay
EWP12	5.17	0.27	0.24	19.66	10.63	2.03	23.71	38.00	30.00	32.00	Clay
BBP13	4.83	1.28	0.67	15.18	5.89	1.28	18.01	18.00	58.00	24.00	SL
BBP14	5.54	0.22	0.16	22.30	14.75	2.15	23.03	41.00	27.00	32.00	Clay
GMP15	4.85	1.38	1.09	14.68	7.14	0.93	17.27	44.00	28.00	28.00	Clay
A61	5.02	1.10	0.98	18.97	8.05	1.86	19.77	43.00	28.00	29.00	Clay
A62	4.51	7.98	6.72	14.73	7.54	1.15	14.62	41.00	30.00	29.00	Clay
A63	4.72	3.57	2.57	15.00	6.77	1.18	16.11	47.00	26.00	27.00	Clay
A71	4.65	4.34	3.71	13.07	6.86	0.44	13.55	57.00	24.00	19.00	CL
A72	4.63	5.86	4.66	11.54	6.89	0.45	13.78	15.00	52.00	33.00	CL
A73	4.61	4.89	4.35	12.87	6.72	0.44	12.79	48.00	28.00	24.00	CL
A74	4.58	4.31	3.70	13.07	6.22	0.46	14.95	38.00	26.00	36.00	CL
A75	4.50	9.36	8.75	13.01	5.91	0.45	13.38	42.00	26.00	16.00	CL
A81	4.61	4.88	4.76	15.02	7.62	1.20	13.96	38.00	28.00	34.00	Clay
BBP1	4.38	8.13	6.32	15.18	5.60	1.28	12.78	42.00	27.00	31.00	Clay
GMP2	4.68	0.82	0.31	13.86	6.53	0.46	23.13	48.00	29.00	23.00	Clay
GMP3	5.18	0.58	0.19	20.30	10.62	2.02	18.42	46.00	31.00	23.00	Clay
BBP4	5.00	0.33	0.21	17.25	9.98	1.80	48.68	36.00	30.00	34.00	CL

EWP5	4.64	5.16	3.89	14.16	7.37	0.52	16.53	34.00	28.00	38.00	Clay
EWP6	4.63	5.92	5.48	14.97	7.82	1.16	13.63	39.00	24.00	37.00	Clay
EWP7	4.87	0.72	0.54	13.25	7.27	0.46	21.17	40.00	26.00	34.00	CL
GMP8	4.46	5.48	3.70	14.14	7.66	0.52	16.76	38.00	33.00	29.00	Clay
EWP9	4.66	3.10	2.16	15.14	7.78	1.22	14.27	42.00	32.00	26.00	Clay
Min.	**4.38**	**0.22**	**0.16**	**11.54**	**5.60**	**0.44**	**12.78**	**15.00**	**24.00**	**16.00**	
Max.	**5.54**	**9.36**	**8.75**	**20.30**	**14.75**	**2.15**	**48.68**	**57.00**	**58.00**	**38.00**	
Mean	**4.77**	**3.47**	**2.81**	**15.24**	**7.76**	**1.12**	**18.35**	**40.58**	**30.00**	**28.75**	
STDV	**0.27**	**2.76**	**2.45**	**2.09**	**1.99**	**0.26**	**7.36**	**9.21**	**8.12**	**5.82**	

Where: EWP= Ebba wakayo profile, BBP= Beryo Bedeso profile, GMP= Gute Michael profile, A= Auger, ex. Acd= exchangeable acidity, ex. Al= exchangeable Al=, Av. P= Available phosphorus, OC= Organic carbon, CEC= Cation Exchange Capacity, PBS= Percentage base saturation, and CL= Clay loam.

Correlation analysis showed strong negative correlation (r= -0.81***) between exchangeable acidity and soil pH (Table 2). Reports also indicate that exchangeable acidity is a function of soil pH and presence compounds such as $Al(OH)^{3+}$ or $Al(OH)^{2+}$, and weak organic acid ions held at the colloid surfaces of the soil (Hinrich *et al.,* 2001). It has inverse relation.

According to London (1991), Cations exchange capacity (CEC) of the soils in the study is also categorized as low to medium (Table 1). This might be due to too low organic matter content and high soil acidity. Blake *et al.,* (1991) and Johnson (2002) reported low CEC for strongly acidic soil. Pearson's simple correlation analysis showed positive correlation (r = 0.40) of CEC with soil exchangeable Al (Table 2). Basically, CEC of soil is determined by the relative amounts and/or type of the two main colloidal substances, humus and clay. Organic matter particularly plays important role in exchange process because it provides more negatively charged surfaces than clay particles.

The mean value of percentage of base saturation (PBS) is very low (Table 1). This could be due to leaching and their continuous losses through harvested parts of plants, which probably the main cause for lower soil pH. Likewise, exchangeable bases readily decreased showing declined of basic cations from the exchange complex of the soil colloids (Jaiyeoba, 2003). Person's simple correlation analysis showed a positive correlation (r = 0.50*) of PBS with soil pH, while negative correlation with exchangeable acidity (r= -0.57**) (Table 2).

 In addition, most soils of the study area are also poor in organic carbon content. This could be due to intensive tillage practices coupled with reduced soil organic matter inputs and almost complete removal of crop residues from cultivated fields. This is in line with several findings (Palm *et al.,* 2001 and Aberha *et al.,* 2012) revealed that low OM content of cultivated soils could be attributed to increased rates of organic matter oxidation, mainly caused by tillage activities, decline in total organic matter inputs, increased soil temperatures due to exposure of the soil surface, increased wetting and drying cycles, and losses by erosion. Person's simple correlation analysis showed a positive correlation (r = 0.74***) of OC with soil pH, while negative correlation with exchangeable acidity (r= -0.52*) (Table 2).

Table 2: Correlation coefficients (r) between soil acidity and other soil properties for 24 Nedjo district soils

	pH	Exch. Acidity	Exch. Al	CEC	Av. P	OC	PBS	Clay
pH	1							
Exch. Acidity	-0.81***	1						
Exch. Al	-0.77***	0.98***	1					
CEC	0.06NS	0.40*	0.41*	1				
Av. P	0.84***	-0.52*	-0.48*	0.20NS	1			
OC	0.74***	-0.52*	-0.50*	0.02NS	0.67***	1		
PBS	0.50*	-0.57**	-0.57**	-0.20NS	0.44*	0.03NS	1	
Clay	0.06NS	-0.10NS	-0.07NS	0.03NS	0.06NS	-0.13NS	-0.07NS	1

***= very highly significant, **highly significant, *=significant, NS= non-significant

According to London (1991), the available P of top soils of the study site is rated as low. This low soil phosphorous might be due to low pH and high exchangeable acidity (Table 1). Hence, phosphorous in the soil solution could be fixed by oxides of Al and Fe as these oxides have high P fixing potential in acid soils. Dawit *et al.,* (2002) who reported that availability of P in most soils of Ethiopia decline by the impacts of fixation as a result of low pH, abundant crop harvest and erosion. Correlation analysis showed strong positive correlation (r = 0.84***) of available P with soil pH, but strong negative correlation (r = -0.52*) soil exchangeable acidity (Table 2). This suggests bioavailability of P in soil of the study site could be increased by increasing soil pH. The specific adsorption of organic anions on hydrous oxides of Fe and Al surfaces and the corresponding release of hydroxyl ions could increase the pH and subsequently available P in the soil solution. Therefore, application of lime and other liming material is mandatory to increase soil pH and subsequently to improved P availability.

Therefore, these and aforementioned chemical properties of the soil coupled with its high level of exchangeable acidity associated with element toxicity on the whole indicate that the fertility status of the experimental soils are lower and the nutrient level is inadequate for successful crop production. Hence, conditioning the soil through some sort of amendment such as lime treatments to enhance its fertility and productivity is immense.

4.2. Lime Requirements (LR) by Various Methods

Table 3 shows the lime requirement to a target pH 6.5 for acidic soils of Nedjo district using different methods. Accordingly, the lime amount to bring the pH to pH 6.5, determined by $Ca(OH)_2$- titration method ranges from 3.26 to 7.20 t/ha, by Shoemaker-McLean-Pratt single buffer (SMP-SB) method from 0.22 to 10.30 t/ha, by Shoemaker-McLean-Pratt double buffer (SMP-DB) method from 2.98 to 7.19 t/ha and by New Woodruff buffer method from 1.73 to 9.64 t/ha

At lime requirements (LRs) above 5.88 ton/ha soil, following the various methods are in the range of 6.05 to 7.20 ton/ha based on the $Ca(OH)_2$- titration method; from 5.82 to 10.30 ton/ha following the SMP-SB method; from 6.15 to 7.20 ton/ha according to the SMP-DB method and 4.90 to 9.64 ton/ha based on the New Woodruff buffer method.

At lime requirements below 5.88 ton/ha soil, following the various methods are in the range of 3.26 to 5.67 ton/ha based on the $Ca(OH)_2$- titration method; from 0.22 to 6.94 ton/ha following the SMP-SB method; from 2.98 to 5.60 ton/ha according to the SMP-DB method and 1.73 to 7.09 ton/ha based on the New Woodruff buffer method.

These results imply that the SMP-SB and New woodruff buffer methods are not sensitive enough for soils of high and low LRs. but SMP-DB is sensitive enough for soils of high and low LRs. The sensitivity is checked by using root mean square error (RMSE) (Table 3). Hence, the SMP-DB method virtually gives the nearly equal lime requirement value where the standard gives a lime requirement range from 2.98 to 7.19 ton/ha for soils of high and low LRs. The sensitivity, however, improves for soils of low and high lime requirements of SMP-DB method. This is in line with Ssali and Nuwamanya (1981) who reported that the SMP-DB method to better predict the mean LR to pH 6.5.

Table 3: Lime requirements (in t/ha soil) of 24 soils to pH 6.5 determined by various methods

Sample code	Ca(OH)$_2$-titration	SMP-SB	SMP-DB	New Woodruff
BBP1	7.20	10.30	7.19	9.23
GMP8	6.93	10.30	7.02	8.57
A75	6.79	9.18	6.80	9.64
A62	6.76	8.06	6.57	9.44
A74	6.52	8.06	6.55	7.70
A73	6.42	8.06	6.45	8.93
A81	6.42	8.06	6.48	7.96
A72	6.35	8.06	6.40	8.72
EWP7	6.35	5.82	6.42	8.52
EWP5	6.32	6.94	6.30	7.04
A71	6.28	6.94	6.32	8.42
EWP9	6.25	8.06	6.34	8.26
GMP2	6.18	6.94	6.15	4.90
A63	6.05	6.94	6.20	8.01
High LR soils (>5.88 ton/ha) Means	**6.49**	**7.98**	**6.51**	**8.24**
Percentage below/above reference		**22.96**	**0.02**	**26.96**
Root mean square error (RMSE)		**1.66**	**0.03**	**1.78**
BBP13	5.67	6.94	6.00	6.89
GMP15	5.61	5.82	5.55	7.09
EWP10	5.57	5.82	5.60	4.90
EWP7	5.54	5.82	5.50	5.71
EWP11	5.40	5.82	5.38	6.38
BBP4	5.10	4.70	5.13	1.73
EWP12	5.03	4.70	5.00	5.66
BBP4	4.52	3.58	4.60	4.85
GMP3	4.48	4.70	4.35	5.41
BBP14	3.26	0.22	2.98	3.93
Low LR soils (<5.88 ton/ha) Means	**5.02**	**4.81**	**5.01**	**5.26**
Percentage below/above reference		**-4.18**	**-0.20**	**4.78**
Root mean square error (RMSE)		**1.00**	**0.09**	**0.24**
Means of all soils	**5.88**	**6.66**	**5.89**	**7.00**
Percentage below/above reference		**13.26**	**0.17**	**19.05**
Root mean square error (RMSE)		**1.96**	**0.002**	**1.68**

SMP-SB= Shoemaker- McLean-pratt single buffer, SMP-SB= Shoemaker- McLean-pratt double buffer,

LR=Lime requirement

For all the 24 soils the mean lime requirement values to pH 6.5 obtained with SMP-DB method was 0.17%, above the obtained with $Ca(OH)_2$-titiration, the values obtained with SMP-SB and New Woodruff buffer methods were 13.26% and 19.05%, respectively, of that obtained with $Ca(OH)_2$-titration. Thus overall the SMP-DB method gives the least variation from the reference method ($Ca(OH)_2$- titration) throughout the entire range.

According to table 4, the lime requirement rates to a pH of 6.0 were found different comparing the buffer methods with the standard ($CaCO_3$-incubation) method. At lime requirements above 5.88 ton/ha soils, following the various methods are in the range of 5.92 to 6.20 ton/ha based on the $CaCO_3$-incubation method; from 8.74 to 8.75 ton/ha following the SMP-SB method; from 5.77 to 5.94 ton/ha according to the SMP-DB method and 8.57 to 9.23 ton/ha based on the New Woodruff buffer method.

At lime requirements below 5.88 ton/ha soil, following the various methods are in the range of 3.47 to 5.78 ton/ha based on the $CaCO_3$-incubation method; from 2.02 to 6.72 ton/ha following the SMP-SB method; from 3.10 to 5.55 ton/ha according to the SMP-DB method and 1.73 to 9.64 ton/ha based on the New Woodruff buffer method.

Once again the SMP-DB method virtually gives the nearly equal lime requirement value where the standard gives a lime requirement range from 3.47 to 6.20 ton/ha. It is highly sensitive for soils of high and low lime requirements with root mean square error (RMSE) 0.22 (Table 4).

The mean lime requirement value to pH 6.0 for soils of high lime requirements (> 5.88 ton/ha soil) obtained with SMP-DB method was 3.30%, below that obtained with $CaCO_3$-incubation, while the values obtained with SMP-SB and New woodruff buffer methods were 44.22% and 46.86% respectively, above of that obtained with $CaCO_3$-incubation.

For soils of low lime requirements (< 5.88 ton/ha soil), the mean lime requirement values to achieve pH 6.0 obtained with SMP-SB and SMP-DB methods were 4.50 and 4.70% respectively, above and below the obtained with $CaCO_3$-incubation,while the values obtained with new Woodruff buffer method was 46.99% above the obtained with $CaCO_3$-incubation.

Table 4: Lime requirement (in ton/ha soil) of 23 soils to pH 6.0 determined by various methods

samples code	CaCO$_3$-Incubation	SMP-SB	SMP-DB	New woodruff
BBP1	6.20	8.74	5.94	9.23
GMP8	5.92	8.74	5.77	8.57
High LR soils >5.88 ton/ha Means	**6.06**	**8.74**	**5.86**	**8.90**
Percentage below/above reference		**44.22**	**-3.30**	**46.86**
Root mean square error (RMSE)		**2.68**	**0.21**	**2.84**
A75	5.78	7.62	5.55	9.64
A62	5.69	6.50	5.32	9.44
A74	5.52	7.62	5.30	7.70
A73	5.42	6.50	5.20	8.93
A81	5.41	6.50	5.23	7.96
A72	5.35	6.50	5.15	8.72
EWP6	5.35	4.26	5.17	8.52
EWP5	5.33	5.38	5.05	7.04
A71	5.27	5.38	5.07	8.42
EWP9	5.26	6.50	5.09	8.26
GMP2	5.18	5.38	4.90	4.90
A63	5.08	5.38	4.95	8.01
BBP13	4.76	5.38	4.75	6.89
GMP15	4.63	4.26	4.30	7.09
EWP10	4.55	4.26	4.35	4.90
EWP7	4.54	4.26	4.25	5.71
EWP11	4.42	4.26	4.13	6.38
BBP4	4.10	3.14	3.88	1.73
EWP12	4.08	3.14	3.75	5.66
A61	3.50	2.02	3.27	4.85
GMP3	3.47	3.14	3.10	5.41
Low LR soils <5.88 ton/ha Means	**4.89**	**5.11**	**4.66**	**6.96**
Percentage below/above reference		**4.50**	**-4.70**	**42.33**
Root mean square error (RMSE)		**0.73**	**0.23**	**2.22**
Means of all soils	**4.99**	**5.43**	**4.76**	**7.13**
Percentage below/above reference		**8.82**	**-4.60**	**42.88**
Root mean square error (RMSE)		**1.01**	**0.22**	**2.28**

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The variation from the reference method ($CaCO_3$-incubation) is thus again the least with SMP-DB method throughout the entire range (for low and high), but the SMP-SB method shows the least variation from the reference at low LRs with higher root mean square error (RMSE) from SMP-DB (Table 4).

Table 5 shows the lime requirement to pH 5.5 of acid soils in Nedjo district using different methods. As presented in Table 5, the lime requirement rates to a pH of 5.5 were found different comparing the buffer methods with the standard ($CaCO_3$-incubation) method.

Table 5: Lime requirements (in ton/ha) of 23 soils to pH 5.5 determined by various methods

Samples code	$CaCO_3$-Incubation	SMP-DB	New woodruff
BBP1	5.21	4.69	9.23
GMP8	4.90	4.52	8.57
A75	4.79	4.30	9.64
A62	4.69	4.07	9.44
A74	4.53	4.05	7.70
A73	4.43	3.95	8.93
A81	4.42	3.98	7.96
A72	4.36	3.90	8.72
EWP6	4.36	3.92	8.52
EWP5	4.34	3.80	7.04
EWP9	4.27	3.84	8.26
A71	4.26	3.82	8.42
GMP2	4.19	3.65	4.90
A63	4.09	3.70	8.01
BBP13	3.78	3.50	6.89
GMP15	3.64	3.05	7.09
EWP7	3.55	3.00	5.71
EWP10	3.53	3.10	4.90
EWP11	3.43	2.88	6.38
BBP4	3.11	2.63	1.73
EWP12	3.09	2.50	5.66
A61	2.51	2.02	4.85
GMP3	2.48	1.85	5.41
Low LR soils <5.88 ton/ha Means	**4.00**	**3.51**	**7.13**
Percentage below reference		**-12.25**	**78.25**
Root mean square error (RMSE)		**0.48**	**3.22**

The lime requirement values to raise soil pH to 5.5 show that $CaCO_3$-incubation method gives a lime requirement range from 2.48 to 5.21 ton/ha for soils of low LRs, SMP-DB method gives a range from 1.85 to 4.69 ton/ha; while New Woodruff method a range from 1.73 to 9.64 ton/ha. These results once again imply SMP-DB method is more sensitive with root mean square error (RMSE = 0.48) than the new woodruff method for soils of low lime requirements.

The mean lime requirement values for soils of LRs to pH 5.5 obtained with SMP-DB was 12.25% below that obtained with $CaCO_3$ – incubation, while the value obtained with New Woodruff method was above 78.25% of that obtained $CaCO_3$-incubation. The least variation from the reference method ($CaCO_3$-incubation) is once more given by the SMP-DB method throughout the low LRs.

For all buffer methods the highest and the lowest indicated lime requirement values (to pH 6.5, 6.0 and 5.5) were for same the soils. These results were consistent with the wide range of acid properties exhibited by these soils. The values of lime requirement to pH 6.5 were approximately twice as large as those to pH 5.5. It is probable that, in addition to exchange acidity were neutralized above this pH levels.

The buffer methods gave different lime requirement ranges for the three targets (pH 6.5, 6.0 and 5.5). Generally, the SMP-DB method gave approximately equal amounts of lime requirement ranges for a given pH target for high and low lime requirements. The SMP-SB method gives highly over and underestimates from the standard methods for high and low lime requirements, while New Woodruff method gives highly overestimates from the standard methods for high and low lime requirements throughout. The results also showed that at the three pH targets the mean lime requirement values obtained with the SMP-DB method generally deviated less from the mean values obtained with the reference methods ($Ca(OH)_2$-titration and $CaCO_3$-incubation) than was the case with other methods. This is in line with Ssali and Nuwamanya (1981) who reported that the SMP-DB method to better predict the mean LR to pH 6.5, 6.0 and 5.5 for Kenya acid soils.

4.3. Regression – Correlation Analysis of various buffer Methods of Lime Requirement and Standard Lime Requirement Methods

Lime requirement values measured by $Ca(OH)_2$-titration to pH 6.5 were plotted against the three buffer indicated values (Fig. 3. a-c); while the regression statistics are presented in table 6. The correlation coefficients (r) were highly significant ($P < 0.05$) for SMP-SB and SMP-DB methods involving the 24 soils, but non-significant for new Woodruff buffer method. The correlation coefficient for SMP-DB method, however, was the highest ($r = 0.98$) (Table 6).

For the SMP-SB method (Fig. 3a) the regression line indicates that this method highly underestimates amount of lime required for soils of low lime requirement, hence a big deviation of the regression line from the ideal line. Furthermore, the uncertainty of measurement indicated by the standard error of estimates (Sy,x) is smaller for this method, but greater than from SMP-DB method (Table 6).
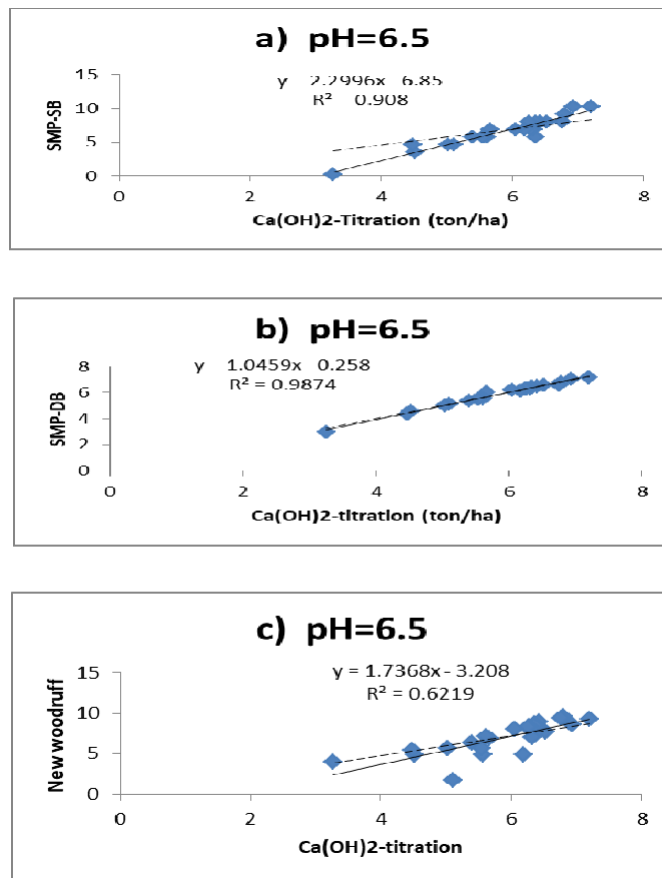
Figure 3: Lime requirements (LR) to pH 6.5 of 24 acid soils as measured by $Ca(OH)_2$-titration verses those measured by various buffer methods.

For the SMP-DB method (Fig. 3 b) the regression line indicates that this method estimates equal amounts of lime for soils of high and low lime requirements as the standard $(Ca(OH)_2$-titration). Thus the deviation of the regression line from the ideal line is less and the standard error of estimate (Sy,x) is also lower and smaller than that for data from the SMP-SB method (Table 6).

Lime requirement values measured by $CaCO_3$ - incubation to pH 6.0 are plotted against those indicated by three buffer methods (Fig. 4 a-c), while the regression statistics are presented in table 6. The correlation coefficients (r) show that they were highly significant (P=0.01) for SMP-SB and SMP-DB methods involving the 23 soils, but non-significant (p<0.05) for New Woodruff buffer method. Once again the correlation coefficient for data for SMP-DB method was the highest (r = 0.98) (Fig. 4 b).

Table 6: Regression statistics for lime requirements indicated by various buffer methods vs. lime requirements measured by $Ca(OH)_2$-titration (to target pH 6.5) and $CaCO_3$-incubation (to target pH 6.0 and 5.5)

No of samples	Reference LR	Methods	Equations	r	Sy,x
24	LR to pH 6.5	SMP-SB	y= 2.2996x-6.85	0.91***	0.68
24	LR to pH 6.5	SMP-DB	y= 1.0459x-0.258	0.98**	0.11
24	LR to pH 6.5	New woodruff	y= 1.7368x-3.208	0.62 NS	1.26
23	LR to pH 6.5	$CaCO_3$-incubation		0.99***	0.03
23	LR to pH 6.0	SMP-SB	y= 2.2771x-5.938	0.85***	0.72
23	LR to pH 6.0	SMP-DB	y= 1.0286x-0.375	0.98**	0.08
23	LR to pH 6. 0	New woodruff	y= 2.0958x-3.333	0.62 NS	1.22
23	LR to pH 5.5	SMP-DB	y= 1.0311x-0.613	0.98***	0.08
23	LR to pH 5.5	New woodruff	y= 2.1036x-1.282	0.62 NS	1.22

*Where: **= significant at P= 0.01 level, *** significant at P = 0.001 level,   NS = not significant at P < 0.05 and Sy,x= standard error*

For the SMP-SB method (Fig. 4 a), the regression line indicates that this method highly overestimates amounts of lime for soils of high and low lime requirements. The deviation of the regression line from the ideal line is, therefore, high especially at low and high lime requirement levels.

The regression line for data for SMP-DB method (Fig. 4 b) indicates that this method estimates approximately equal amounts of lime for soils of high and low lime requirements as the standard ($CaCO_3$-incubation). Thus the deviation of the regression line from the ideal line is less and the standard error of estimate (Sy,x) is also lower and smaller than that for data from the SM-SB (Table 6).

a) pH=6.0

$y = 2.2771x - 5.938$
$R^2 = 0.8499$

b) pH=6.0

$y = 1.0286x - 0.375$
$R^2 = 0.9889$
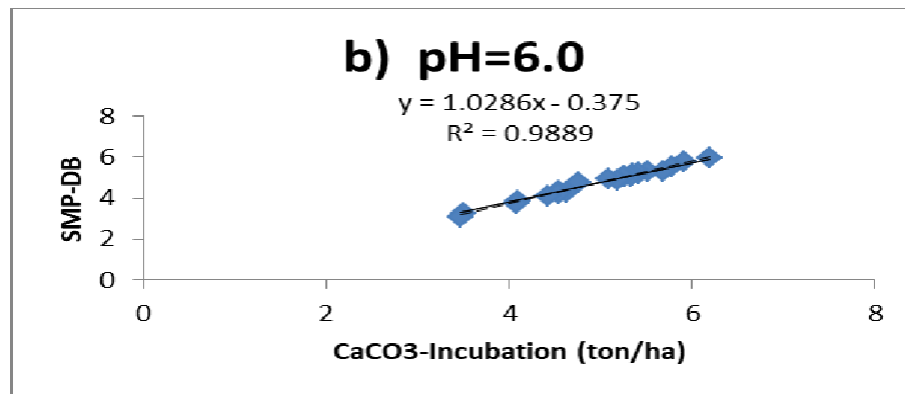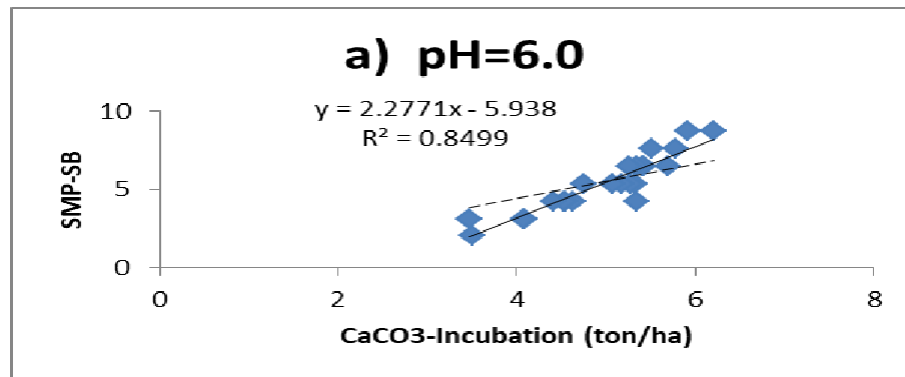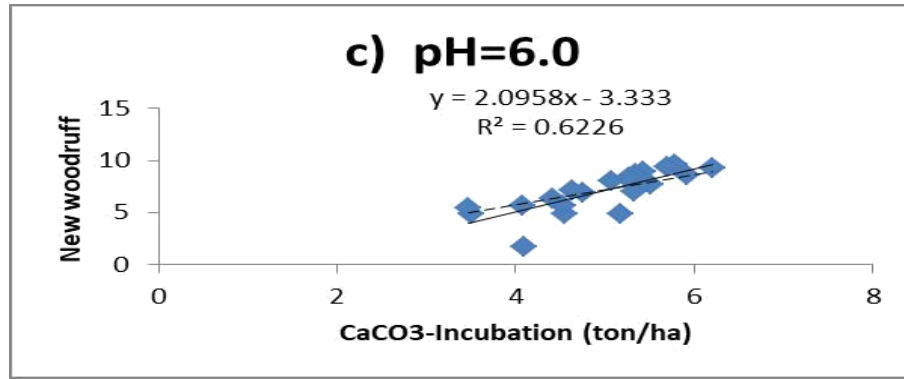
Figure 4: Lime requirements (LR) to pH 6.0 of 23 acid soils as measured by $CaCO_3$-incubation vs. those indicated by various buffer methods.

Lime requirement values measured by $CaCO_3$-incubation to pH 5.5 are plotted against the values obtained with the buffer methods (Fig. 5a-b) while the regression statistics are presented in table 6. Once again the correlation coefficients (r) was highly significant (P= 0.001) for SMP-DB method involving the 23 soils. The correlation coefficient for data for SMP-DB was again the highest (r= 0.98). The regression line (Fig. 5a) for SMP-DB method indicates that this method estimates approximately equal amounts of lime as the standard ($CaCO_3$-incubation) throughout the entire range, but slightly underestimates for soils low lime requirements. Hence, the deviation of the regression line from the ideal line is very small throughout the lime requirement range with very small standard error of estimate (Sy, x) in table 6.
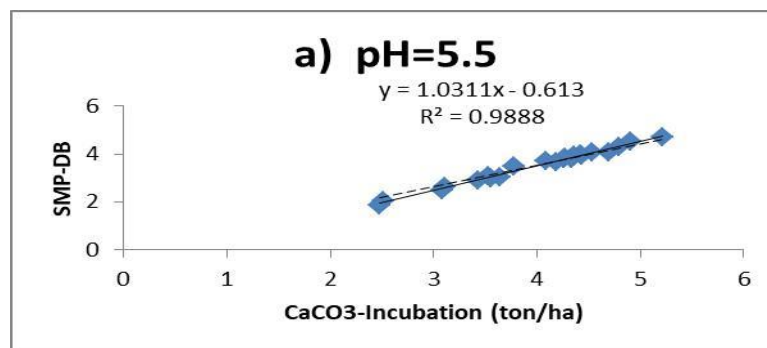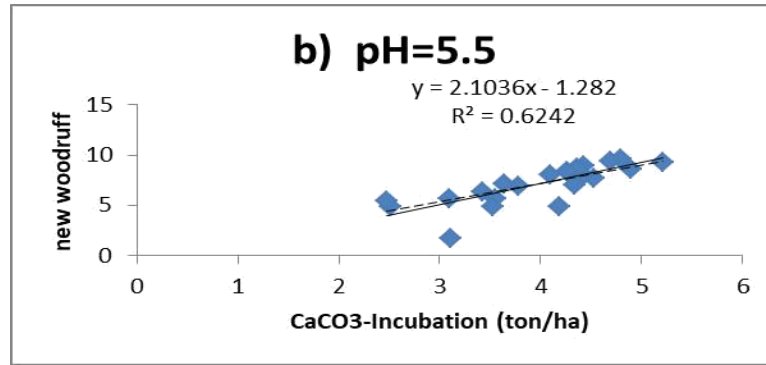
Figure 5: Lime requirements (LR) to pH 5.5 of 23 acid soils as measured by $CaCO_3$-incubation vs. those indicated by various buffer methods.

The relatively higher correlation coefficients for data for SMP-DB method at the three pH targets (pH 6.5, 6.0 and 5.5) in this study is consistent with the findings of McLean *et al.,* (1978). They reported higher correlation coefficients for data for SMP-DB (r= 0.956) than for data for SMP-SB (r= 0.550) methods. The correlation coefficient values for data for the buffer methods in this study, however, were generally higher than those reported (McLean *et al.,* 1978). There was generally lack of enough sensitivity in the SMP-SB and New Woodruff methods for soils of high and low lime requirements indicating that these methods might be inadequate for these soils. On the other hand, the SMP-DB method gave the least variation from the reference methods and the highest correlation coefficients at all the three pH targets. These results indicate that this method might be the best choice as a lime requirement index for these soils.

4.4. Effects of Soil Properties on Reference Lime Requirements.

Various soil properties were correlated with lime requirement values measured by $Ca(OH)_2$-titration (to pH 6.5) and $CaCO_3$-incubation (to pH 6.0 and 5.5). Correlation coefficients (r) are presented in table 7. These show that lime requirements to all the three pH targets (pH 6.5, 6.0 and 5.5) were significantly correlated (P=0.0001) with soil pH, Exchangeable acidity, Cation exchange capacity (CEC) and organic carbon (Table 7). In all cases the highest correlation coefficients with lime requirements were for soil pH, followed by exchange acidity. This is in line with Ssali and Nuwamanya. (1981), who reported that the exchangeable acidity (r=0.96***) and exchangeable Al (r=0.83***) were positively significantly correlated with each and negatively correlated with soil pH in Kenya acid soils.

Table 7: Correlation coefficients (r) for reference lime requirements vs. soil properties

Soil properties	LR to pH 6.5 (24 soils) +	LR to pH 6.0 (23 soils) ++	LR to pH 5.5 (23 soils) ++
Soil pH	-0.98***	-0.97***	-0.97***
Soil Organic Carbon	-0.73***	-0.70***	-0.69***
Exchangeable Acidity	0.80***	0.82***	0.84***
Exchangeable Al	0.76**	0.78***	0.80***
CEC	-0.84***	-0.77***	-0.76***
PBS	-0.49*	-0.52*	-0.52*
Av. P	-0.81***	-0.69*	-0.69***
Clay	-0.07NS	-0.10NS	-0.10NS

Where: + = as measured by Ca(OH)$_2$-titration,   ++= as measured by CaCO$_3$-incubation
*   **= significant at P= 0.01 level,   NS = not significant at P < 0.05.*

From (Table 7) above there was highly significant (p=0.0001) negative correlation between reference lime requirements and soil pH, and positive correlation with exchangeable acidity and exchangeable Al. This indicates that the amount of lime required to reclaim acid soil increases soil pH and exchangeable bases and decreases soil acidity (exchangeable Al and H). As a result aluminum toxicity will be decreased and available plant nutrients will be increased. In line with my result, McLean (1978) observed a large drop in the soil–buffer pH per unit increase in LR and attributed this to the pH-dependent acidity being much greater at higher soil pH values in this high soil–buffer pH range, causing a larger than expected drop in buffer pH.

This relationship between lime requirements and soil properties (Table 7) is similar to observations elsewhere. Webber *et al.,* (1977) also observed that lime requirements to pH 6.0 and 5.5 of Canadian soils correlated highly with exchangeable aluminum (r= 0.80, 0.82) and exchange acidity (r= 0.92, 0.82). The relatively high correlation coefficients between the amount of lime required raising soil pH to 6.5, 6.0 and 5.5; exchangeable acidity and Al, CEC, Organic carbon and soil pH in this study indicate that these soil properties contribute to lime requirement of the target soils. The higher correlation coefficient values for all the three

pH targets suggest that initial pH, exchangeable acidity, CEC and organic carbon should be considered when estimating the lime requirements of these soils. These results indicate that the LR determination of acid soils is affected by soil buffer equilibration and chemical properties that are associated with acidity factors and buffer capacity. These results are consistent with Machacha (2004) who evaluated the ability of several buffer methods including SMP and Adam-Evans single methods to predict the actual LR of acid soils of the eastern region of Botswana to pH 6.5. He found that the buffer capacity, organic carbon, exchangeable acidity and Al were the most important soil properties influencing LR of acid soils in eastern Botswana.

4.5. Effect of Liming on soil pH and Exchangeable Acidity.

Exchangeable acidity decreases with increasing lime rate at all pH levels for all soils (Table 8). Liming increased Ca^{2+}, percentage base saturation, and decreased exchangeable Al^{3+}. This is why the activity of Al^{3+} is reduced by precipitation as $Al(OH)_3$. Opala (2017), recommended application of 2 t CaO ha^{-1} of lime use in soils of Western Kenya was adequate to alleviate Al toxicity. Application of lime highly decreased exchangeable acidity and Al^{3+}, as the level of applied lime rates increased. This result was similar to those obtained by Hirpa *et al.* (2013) who reported that with application of 9 t ha^{-1} lime the pH of the soil increased from 4.45 to 5.14, and the exchangeable acidity reduced from 5.19 to 0.39 Cmolc-kg^{-1} soil.

Susolski (2004) reported exchangeable Al^{+3} as 2.76 ± 0.17 and total exchangeable acidity as 3.19 ± 0.93 Cmolc-Kg-1 soils. So, high exchange between acid cations (Al^{+3} and H^{+}) and basic cations (Na^{+}, K^{+}, Ca^{+2}, and Mg^{+2}) is expected and Al^{+3} toxicity may affect the availability of basic cations especially during plant roots uptake of the nutrients.

4.6. Pot Experiment

The Vertic Luvisols (A61) and Rhodic Nitisols (EWP5) were used in lath-house in the pot study (Table 1). Establishment of plants was generally good in the two soils used for the pot experiment. In the case of Rhodic Nitisols, especially at low pH level, plants didn't establish well and were not healthy. They were rather stunted and showed small and wrinkled leaves and stems especially at low lime levels than Vertic Luvisols (Figure 6).

Figure 6: Photo taken for the observation of root and stem in the pot experiment.

Application of 8 t ha^{-1} lime increased soil pH from 4.64 to 6.62 for Rhodic Nitisols and 6 t ha^{-1} lime increased soil pH from 5.02 to 6.44 for the Vertic Luvisols (Table 9 and 10). This result is in line with Buni (2014) who reported that soil pH increased significantly from 5.03 in the plots without lime to 6.72 at the lime rate of 3.75 $CaCO_3$ t ha^{-1}. This indicated that when lime is added to acid soils that contain high exch. Al^{3+} and H^+ concentrations, it dissociates into Ca^{2+} and OH^- ions. The hydroxyl ions will react with H^+ and Al^{3+} ions forming aluminum hydroxide ($Al(OH)_3$) and water (H_2O); thereby, increasing soil pH in the soil solution.

Exchangeable acidity and Al contents of the soil were decreased in response to the application of lime (Table 9 and 10). The highest exchangeable Al (3.93 and 0.64 Cmolckg^{-1}) and acidity (5.17 and 2.43 Cmolckg^{-1}) were recorded on the control pots of soil in Rhodic Nitisols and Vertic Luvisols, respectively. This might be due to increased replacement of Al^{3+}
by Ca^{2+} in

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the exchange site and subsequent precipitation of Al, as $Al(OH)_3$, due to liming of the soil. This result is in line with Agegnehu *et al.* (2006) who reported that soil pH consistently increased from 4.37 to 5.91 as lime rate increased. Conversely, the exchangeable acidity was significantly reduced from 1.32 to 0.12 $Cmolckg^{-1}$ because of lime application.

The effect of liming on wheat plant height was statistically significantly different and the application of different lime rates significantly increased plant height for both soils (Table 9 and 10). The plant height ranged from 28.47 cm to 52.07 cm for Vertic Luvisols and 20.23 to 52 cm for Rhodic Nitisols. The highest plant height was obtained from 4 t ha^{-1} on Vertic Luvisols and 8 t ha^{-1} on Rhodic Nitisols, and the grain yield was also high for the same treatments 5.60 g/pot and 4.21g/pot, respectively.

Spike length of wheat was found significantly different due to the increasing amount of lime application both soils types (Table 9 and 10). Spike length of wheat ranged from 4.43 to 5.39cm for Verti Luvisols and 2.19 to 3.54cm for Rhodic Nitisols, and tallest spike length was found in 4 t ha^{-1} and 6 t ha^{-1}, respectively. The grain yield of wheat also positively correlated with spike length characters.

Table 8: Effect of liming on some soil properties and the mean plant height, spike length and biomass of wheat in Rhodic Nitisols (EWP5) in the pot studies

CaCO$_3$ added (in ton/ha soil)	Soil pH	Exch. Acidity	Exch. Al	Mean Plant height	Spike length	Dry Biomass	Grain yield
		($Cmolckg^{-1}$)		(in cm/5 plants)		(g/pot)	
0	4.64[d]	5.17[a]	3.93[a]	20.23[c]	2.19[c]	5.92[d]	2.18[d]
4	5.42[c]	3.22[b]	2.06[b]	27.67[b]	2.62[b]	7.52[c]	2.76[c]
6	6.14[b]	1.52[c]	1.08[c]	51.00[a]	3.54[a]	10.87[a]	4.21[a]
8	6.62[a]	0.85[d]	0.57[d]	52.00[a]	3.37[a]	9.42[b]	3.56[b]
CV	0.18	1.37	4.38	1.71	2.94	5.46	5.00
LSD	0.02	0.07	0.17	1.29	0.17	0.92	0.92

Where: CV= Coefficient of variance, LSD= Least Significant Difference

Grain yield of wheat was significantly affected by different rates of lime (Table 9 and 10). The highest grain yield was obtained from 4 t ha^{-1} and 6 t ha^{-1} lime while the lowest was from controls (zero lime applied) in Vertic Luvisols and Rhodic Nitisols, respectively. The lime rate significantly increased the grain yield of wheat to control treatments.

Table 9: Effect of liming on some soil properties and the mean plant height, spike length and biomass of wheat in Vertic Luvisols (A61) in the pot studies

CaCO$_3$ added (in ton/ha soil)	Soil pH	EA	EAl	Plant height	Spike length	Dry Biomass	Grain yield
		(Cmolckg^{-1})		in cm/5 plants		(g/pot)	
0	5.02[d]	2.43[a]	0.64[a]	28.47[c]	4.43[c]	8.13[d]	3.37[d]
2	5.48[c]	1.68[b]	0.47[ba]	40.67[b]	4.85[b]	10.09[c]	4.17[c]
4	5.99[b]	0.92[c]	0.38[ba]	52.07[a]	5.39[a]	15.16[a]	5.60[a]
6	6.44[a]	0.24[d]	0.15[b]	51.73[a]	5.21[a]	12.48[b]	4.95[b]
CV	**0.18**	**2.25**	**5.83**	**2.47**	**2.29**	**4.60**	**5.52**
LSD	**0.02**	**0.06**	**0.48**	**2.14**	**0.23**	**1.05**	**0.50**

Where: EA= Exch. Acidity, EAl= Exch. Aluminum, CV= Coefficient of variance, LSD= Least Significant Difference

Wheat grain yield (g/pot) was positively correlated with plant height and spike length, and it was also affected by changes in soil properties due to liming. The finding is in line with Caires *et al.* (2006) who reported that surface liming caused increases up to 140% in the grain yield of wheat.

For both soil types, wheat plant height, spike length and grain yield were significantly (p=0.001) increased with the increase in pH as lime rates increased and then decreased at higher pH levels by using SMP-DB method (Table 9 and 10). This result implies that the study area acid soils were lime up to pH 6.0 is enough for the specific crop. In the table 9 and 10 the results also imply that application of lime beyond maximum pH levels causes nutrient imbalance. In view of these results, therefore, it would be advantageous not only to know the conditions of soils but also to understand the influence of lime on the crop to be grown. The application of lime in amounts more than necessary for optimum growth of a particular crop may not only lead to reduced production but also to the waste of the farmers' money. Based on this the optimum pH for the area to ameliorate the acidity of the study site was pH 6.0.

5. CONCLUSIONS AND RECOMMENDATIONS

The result of the present study showed that the soils in Nedjo district are characterized as very strongly to strongly acidic. The soils of the study area were also characterized as low to medium CEC, poor in organic matter or organic carbon and low available phosphorous. The concentration of exchangeable acidity ($Al^{3+} + H^{+}$) and exchangeable Al^{3+} were high, and this indicates that Al toxicity was a problem in the area.

Lime requirement was influenced by some chemical soil properties, particularly exchangeable acidity and Al, organic carbon, CEC and initial soil pH. As soil exchangeable Al/acidity forms increases, the amount of lime required to neutralize acidity increases. The correlation analysis also indicates that the lime requirements for the three pH targets were highly and positively correlated with exchangeable Al/acidity, while negatively correlated with initial soil pH, cations exchange capacity and soil organic carbon. But there was weak correlation with clay content of the soils in the study areas. This indicates that during lime requirement determination these soil chemical properties must be considered.

The evaluated buffer methods by using $Ca(OH)_2$-titration to pH 6.5 and $CaCO_3$- incubation to pH 6.0 and 5.5 as reference methods through regression analysis by using 24 acid soils in study areas. The regression analysis results indicated that lime requirement values measured by the reference methods ($Ca(OH)_2$ –titration to pH 6.5 and $CaCO_3$-incubation to pH 6.0 and 5.5) were well correlated with the values measured by the three buffer methods. The lime requirements to the three pH targets (6.5, 6.0 and 5.5) measured by the buffer methods were also well correlated with amounts of exchangeable aluminum, exchange acidity, cations exchange capacity, soil organic carbon and soil pH.

The SMP-DB method, however, gave the highest correlation coefficient values with the reference methods, the least variation from the ideal line for all the three pH targets. The sensitivity of the SMP-DB method for soils of high and low lime requirements for the three pH targets was high, while lime requirement values measured by SMP-SB and new Woodruff methods indicated that these methods were not sensitive enough for soils of high and low lime requirements. The SMP-DB method is sensitive enough for soils of high and low lime requirements in Nedjo distirict acid soils.

Different lime rates were applied on two selected soil types based on determined pH in the laboratory. Based on these the highest yield components and yields were obtained at pH 5.99 by applying 6 t ha^{-1} and 6.14 by applying 4 t ha^{-1} in Rhodic Nitisols and Vertic Luvisols, respectively. Application of lime increased grain yield of wheat to a considerable extent but application of lime at the rates of 4.0 t ha^{-1} and 6 t ha^{-1} were optimum for desired yield of wheat in the Vertic Luvisols and Rhodic Nitisols in the study area, respectively. In view of these results, therefore, it was concluded that liming of these soils by using SMP-DB method to achieve pH up to 6.0 would be sufficient.

Although SMP-DB method was highly sensitive for soils of high and low lime requirements and gave higher correlation coefficients with reference methods and least variations from the ideal lines. In view of these results, the SMP-DB method recommended to be the best choice as a method of estimating lime requirements for Nedjo district acid soils. Therefore, farmers may need to apply optimum lime to the soils for increase crop productivity the SMP-DB method is recommended.

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7. APPENDICES

Appendix Table 1: Mean monthly temperature (^{0} C) and rainfalls (mm) of Study Area for the years from 2014 to 2018 G.C.

Month	Max-temp.	Min-temp.	Average temp.	Average rain fall
January	28.00	8.40	18.20	0.00
February	29.50	10.62	20.06	2.90
March	29.72	12.50	21.11	20.16
April	28.50	13.34	20.92	59.96
May	26.00	14.42	20.21	260.10
June	24.22	14.00	19.11	377.46
July	22.80	14.08	18.44	346.98
August	22.90	13.36	18.13	303.50
September	23.94	13.32	18.63	316.72
October	24.72	12.78	18.75	127.82
November	21.08	12.12	16.60	23.30
December	27.36	9.62	18.49	3.20
Mean	25.73	12.38	19.05	153.51

Source: National Meteorological Agency, Nedjo station (2019).

Appendix Table 2: Description of experimental sites/ location.

Sample codes	Latitude	Longitude	Altitude (m.a.s.l)
A61	9° 27' 04" N	35° 27' 43" E	1827
GMP2	9° 26" 33" N	35° 27' 26" E	1790
GMP15	9° 27' 03" N	35° 27' 19" E	1810
A72	9° 27' 40" N	35° 27' 46" E	1868
EWP12	9° 26' 30" N	35° 24' 30" E	1931
BBP1	9° 26' 33" N	35° 27' 26" E	1890
EWP11	9° 26' 17" N	35° 24' 05" E	1839
EWP6	9° 26' 15" N	35° 25'45" E	1848
BBP13	9° 25' 35" N	35° 25'22" E	1805
BBP14	9° 26' 30" N	35° 26'40" E	1816

GMP3	9° 27' 00" N	35° 26'30" E	1822
A73	9° 27' 40" N	35° 26'30" E	1873
EWP9	9° 28' 21" N	35° 26' 10" E	1901
A75	9° 28' 42" N	35° 26' 25" E	1912
A81	9° 28' 07" N	35° 26' 05" E	1878
EWP10	9° 12' 10" N	35° 49' 35" E	1885
A62	9° 28' 10" N	35° 27' 20" E	1880
A63	9° 29' 10" N	35° 27'10" E	1905
EWP7	9° 28' 19" N	35° 28' 14" E	1851
GMP8	9° 28' 17" N	35° 27'30" E	1924
EWP5	9° 33' 04" N	35° 26'32" E	1934
A71	9° 29' 42" N	35° 28'22"E	1867
BBP4	9° 30' 31" N	35° 28' 20"E	1831
A74	9° 29' 31" N	35° 28' 56" E	1912

Source: GPS data recorded in 2018/19

Appendix Table 3: Calibration to determine lime requirement of the surface 20 cm of soil using the SMP single buffer method (Sims, 1996)

Soil-buffer pH	Quantity of liming material in tons/ha required to reach target pH				
	Mineral Soils				Organic Soils
	7.0	7.0	6.5	6.0	5.2
	Pure CaCO₃	Ag-ground Limestone ‡			
6.8	2.4	3.2	2.7	2.3	1.5
6.7	4.1	5.3	4.7	3.8	2.9
6.6	5.3	7.6	6.5	5.3	4.0
6.5	7.0	10.1	8.5	7.0	5.3
6.4	9.0	12.3	10.5	8.5	6.5
6.3	10.5	14.6	12.3	10.1	7.8
6.2	12.1	16.8	14.3	11.6	9.0
6.1	13.4	19.2	16.1	13.2	10.3
6.0	15.2	21.5	18.1	14.8	11.4
5.9	17.2	23.8	20.1	16.3	12.8
5.8	18.6	26.2	21.9	17.9	13.9
5.7	20.1	28.5	23.9	19.5	15.0
5.6	21.8	30.6	26.0	21.0	16.3
5.5	23.3	33.2	28.0	22.8	17.5
5.4	25.3	35.4	30.0	24.4	18.8
5.3	26.7	37.8	31.8	26.0	19.9
5.2	28.5	40.1	33.8	27.6	21.0
5.1	30.2	42.5	35.8	29.1	22.4
5.0	31.8	44.8	37.8	30.6	23.5
4.9	33.6	47.2	39.9	32.3	24.7
4.8	34.9	49.5	41.6	33.8	26.0

‡ Limestone with a neutralising value of more than 90%.

Appendix Table: 4 Mean squares of ANOVA for (Vertic Luvisols and Rhodic Nitisols types) some selected soil properties and plant height, spike length, dry biomass weight of wheat crop at Nedjo district.

Vertic Luvisols types (A61)

Source	DF	Mean Square						
		Av. Plant height	Av. Spike length	Biomass dry we.t	Grain yield	Soil pH	Exch. Acidity	Exch. Al
TRT	3.00	374.92	0.53	27.71	2.80	1.14	2.69	0.12
REP	2.00	0.02	0.02	1.29	0.04	0.00	0.00	0.05
Error	6.00	1.14	0.01	0.28	0.06	0.00	0.00	0.06
CV		2.74	2.28	4.60	5.52	0.18	2.25	5.83

Rhodic Nitisols type

Source	DF	Mean Square						
		Average. Plant height	Average. Spike length	Biomass dry we.t	Grain yield	Soil pH	Exch. Acidity	Exch. Al
TRT	3.00	787.13	1.21	14.06	2.38	2.27	11.19	6.55
REP	2.00	0.37	0.01	0.35	0.01	0.00	0.00	0.03
Error	6.00	0.42	0.01	0.21	0.03	0.00	0.00	0.01
CV		1.71	2.93	5.46	5.00	0.18	1.37	4.38

Appendix Table 5: Effect of Liming on soil pH and Exchangeable Acidity

Sample codes	soil properties	Lime levels in ton/ha							
		0	2	4	6	8	10	12	14
EWP10	pH	4.86	5.31	5.81	6.34	6.79	7.45	8.11	8.67
	Exch. acidity (me/100 g)	2.46	2.02	1.84	1.03	0.82	0.42	0.11	0.09
	Exch. Al. (me/100 g)	1.43	1.19	0.89	0.65	0.55	0.35	0.08	0.05
EWP11	pH	4.91	5.29	5.67	6.05	6.43	6.81	7.19	7.57
	Exch. acidity (me/100 g)	1.02	0.94	0.67	0.46	0.28	0.11	0.08	0.04
	Exch. Al. (me/100 g)	0.90	0.82	0.58	0.39	0.20	0.10	0.06	0.02
A61	pH	5.02	5.49	5.99	6.44	6.89	7.34	7.79	8.24
	Exch. acidity (me/100 g)	1.10	0.96	0.75	0.56	0.42	0.16	0.09	0.05
	Exch. Al. (me/100 g)	0.98	0.84	0.66	0.44	0.38	0.13	0.07	0.02
BBP13	pH	4.83	5.29	5.75	6.31	6.67	7.13	7.59	8.05
	Exch. acidity (me/100 g)	1.28	1.08	0.92	0.65	0.43	0.18	0.07	0.04
	Exch. Al. (me/100 g)	0.67	0.98	0.82	0.60	0.39	0.15	0.05	0.02
GMP15	pH	4.85	5.25	5.64	6.04	6.42	6.80	7.18	7.56
	Exch. acidity (me/100 g)	1.38	1.02	0.98	0.71	0.54	0.39	0.09	0.06
	Exch. Al. (me/100 g)	1.09	0.97	0.85	0.62	0.42	0.27	0.07	0.04
EWP12	pH	5.17	5.71	6.25	6.79	7.33	7.87	8.41	8.95
	Exch. acidity (me/100 g)	0.27	0.24	0.14	0.10	0.08	0.06	0.04	0.02
	Exch. Al. (me/100 g)	0.24	0.20	0.12	0.09	0.07	0.04	0.03	0.01
A62	pH	4.51	5.02	5.43	6.23	6.45	7.05	7.45	8.13
	Exch. acidity (me/100 g)	7.98	6.65	5.31	3.53	2.26	1.75	1.04	0.10
	Exch. Al. (me/100 g)	6.72	5.35	4.42	2.23	1.13	0.93	0.09	0.05
A63	pH	4.72	5.10	5.49	6.36	6.74	7.12	7.50	7.88
	Exch. acidity (me/100 g)	3.57	2.89	1.76	1.38	0.97	0.45	0.08	0.03
	Exch. Al. (me/100 g)	2.57	2.02	1.66	1.00	0.78	0.43	0.07	0.01
A71	pH	4.65	5.00	5.38	6.21	6.57	6.93	7.29	7.65
	Exch. acidity (me/100 g)	4.34	3.54	2.92	1.98	1.07	0.84	0.54	0.21
	Exch. Al. (me/100 g)	3.71	2.95	1.93	0.99	0.72	0.54	0.23	0.05
A72	pH	4.63	5.04	5.45	6.12	6.52	6.92	7.32	7.72

	Exch. acidity (me/100 g)	5.86	4.96	3.88	2.72	1.68	1.00	0.07	0.02
	Exch. Al. (me/100 g)	4.66	3.83	2.93	1.84	1.08	0.78	0.05	0.01
A73	pH	4.61	4.97	5.34	6.18	6.54	6.90	7.27	7.62
	Exch. acidity (me/100 g)	4.89	3.65	2.73	1.97	1.22	0.89	0.08	0.05
	Exch. Al. (me/100 g)	4.35	3.43	2.16	1.39	0.97	0.70	0.06	0.01
A74	pH	4.58	4.95	5.31	6.15	6.52	6.89	7.26	7.73
	Exch. acidity (me/100 g)	4.31	3.45	2.51	1.99	1.06	0.93	0.56	0.09
	Exch. Al. (me/100 g)	3.70	2.05	1.37	1.09	0.89	0.62	0.20	0.06
A75	pH	4.50	4.97	5.43	6.09	6.57	7.05	7.53	8.01
	Exch. acidity (me/100 g)	9.36	7.41	6.34	4.99	3.24	1.98	1.21	0.90
	Exch. Al. (me/100 g)	8.75	6.14	5.21	4.09	2.26	1.69	0.94	0.74
A81	pH	4.61	4.98	5.34	6.08	6.45	6.82	7.19	7.56
	Exch. acidity (me/100 g)	4.88	3.56	2.45	1.62	1.01	0.82	0.60	0.41
	Exch. Al. (me/100 g)	4.76	3.32	2.31	1.43	0.84	0.61	0.50	0.20
BBP1	pH	4.38	4.75	5.12	6.10	6.58	7.06	7.54	8.02
	Exch. acidity (me/100 g)	8.13	6.21	5.09	3.45	2.43	1.32	0.43	0.08
	Exch. Al. (me/100 g)	6.32	5.34	4.76	2.32	1.52	1.04	0.22	0.03
GMP2	pH	4.68	5.10	5.45	6.34	6.72	7.10	7.42	7.82
	Exch. acidity (me/100 g)	0.82	0.66	0.49	0.37	0.28	0.16	0.08	0.04
	Exch. Al. (me/100 g)	0.31	0.25	0.20	0.17	0.10	0.07	0.03	0.01
GMP3	pH	5.18	5.51	5.84	6.20	6.50	6.83	7.16	7.50
	Exch. acidity (me/100 g)	0.58	0.41	0.38	0.29	0.13	0.08	0.05	0.02
	Exch. Al. (me/100 g)	0.19	0.10	0.07	0.05	0.02	0.00	0.00	0.00
BBP4	pH	5.00	5.32	5.64	6.00	6.28	6.60	6.92	7.24
	Exch. acidity (me/100 g)	0.33	0.31	0.29	0.20	0.12	0.07	0.04	0.01
	Exch. Al. (me/100 g)	0.21	0.17	0.13	0.09	0.05	0.01	0.00	0.00
EWP5	pH	4.64	5.02	5.42	6.14	6.52	6.90	7.28	7.66
	Exch. acidity (me/100 g)	5.16	4.20	3.09	2.21	1.60	1.00	0.70	0.40
	Exch. Al. (me/100 g)	3.89	2.77	2.13	1.97	1.03	0.80	0.50	0.30
EWP6	pH	4.63	5.01	5.43	6.18	6.48	6.87	7.20	7.54
	Exch. acidity (me/100 g)	5.92	4.81	3.21	2.13	1.12	0.80	0.51	0.09

	Exch. Al. (me/100 g)	5.48	4.23	3.03	2.12	1.10	0.72	0.40	0.07
EWP7	pH	4.87	5.04	5.23	6.26	6.58	6.69	7.01	6.06
	Exch. acidity (me/100 g)	0.72	0.59	0.45	0.30	0.21	0.06	0.00	0.00
	Exch. Al. (me/100 g)	0.54	0.47	0.30	0.20	0.12	0.02	0.00	0.00
GMP8	pH	4.47	4.87	5.26	6.09	6.45	6.86	7.24	7.59
	Exch. acidity (me/100 g)	5.48	4.16	3.12	2.06	1.04	0.69	0.10	0.04
	Exch. Al. (me/100 g)	3.70	2.47	1.98	1.07	0.80	0.44	0.07	0.03
EWP9	pH	4.66	5.12	5.48	6.17	6.58	6.85	7.18	7.61
	Exch. acidity (me/100 g)	3.10	2.09	1.45	1.06	0.50	0.09	0.05	0.03
	Exch. Al. (me/100 g)	2.16	1.36	0.75	0.56	0.40	0.06	0.02	0.01

Where: exch. =exchangeable, exch. Al= exchangeable Aluminum

Appendix Table 6: CaCO3 - incubation curves used to determine lime requirements for different soil samples.

A75

GMP2

GMP3

BBP4

EWP5

EWP6

EWP7

GMP8

EWP9