

**EFFECT OF THE FORM OF AGRICULTURAL LIME ON NEUTRALIZING  
SOIL ACIDITY AND SOYA BEANS (*Glycine max L.*) YIELD ON TWO  
ZAMBIAN ALFISOLS**

**By  
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**A dissertation submitted to the University of Zambia in partial fulfilment of the  
requirement for the degree of Master of Science in Integrated Soil Fertility  
Management.**

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## DECLARATION

I, **Lewis Chiwele**, do declare that this dissertation which I hereby submit for Master of Science in Integrated Soil Fertility Management at the University of Zambia was written and compiled by myself and the work presented herein was as a result of my own research and has not been previously submitted by me for a degree at this or any other institution.

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## APPROVAL

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## ABSTRACT

Soil acidity is a common constraint to crop production in Zambia. Agricultural lime is applied in dry powder form to acid soils to neutralize acidity. New liming materials in aqueous suspension form have recently been introduced on the Zambian market and their effectiveness in neutralizing acidity has not been tested. A study was conducted to assess whether the form in which lime is applied to soil affects its effectiveness in neutralizing acidity and its effect on Soya bean yield. Two strongly acid Alfisols, Choma and Chakunkula Soil Series with pH values of 4.02 and 4.32; exchangeable  $\text{Al}^{3+}$  levels of 0.26 and 0.15 cmol (+)/kg and Al saturation levels of 19 % and 9.5 % , respectively were used as test soils. Four liming materials comprising 3 dry powder forms and one in aqueous suspension were acquired and their neutralizing values were determined. Aqueous suspensions were also made for each dry powder material, to give 4 aqueous samples and 3 dry powder samples for testing. Lime requirements of the two soils were calculated using the formula  $2 \times \text{exch Al}^{3+}$  as the lime requirement. The lime requirements were 850 and 500 kgCaCO<sub>3</sub>/ha for Choma and Chakunkula Soil Series, respectively. Three kilograms of disaggregated soil were mixed with the 7 lime materials corresponding to the lime requirement for each soil. They were kept moist in plastic pots at room temperature for 12 weeks. Soil pH and exchangeable acidity were measured weekly in the first 5 weeks and fortnightly thereafter. The effect of the form of liming material on Soya bean yield was determined in field trials on the two soils. A Randomized Complete Block Design with eight treatments which comprised of 7 lime materials and a control without lime. Powder lime was broadcast on each plot and incorporated into the soil using hand hoes. Aqueous suspensions were prepared by mixing the mass of dry lime required per plot with 8 litres of water and applying them onto the plots using watering cans. Soya bean, was planted in rows 45cm apart after applying Compound D fertilizer ( 10: 20:10) at a rate of 200 kg/ha. Upon maturity, the crop was harvested and the grain yield was measured and recorded. The results showed that lime in aqueous suspension was more effective in raising soil pH than lime in dry powder form on both soils. It took less time to raise the soil pH to 5.5 with lime in aqueous suspension than with lime in dry form on both soils. On Choma soil, lime in aqueous suspension was more effective than lime in powder form in reducing exchangeable acidity. No significant difference was observed in the effectiveness of the two forms of lime in reducing exchangeable acidity on Chakunkula soil series. No significant differences in Soya bean yield were observed between plots treated with lime in aqueous suspension and those with lime in dry powder form at both sites. A greater increase in Soya bean grain yield was observed in limed plots on Choma soil series which had an initial Al saturation of 19 % than on Chakunkula soils which had an initial Al saturation of 9.5 %. Yield increases of 43 % for lime in aqueous suspension and 27 % for lime in dry powder form were obtained on Choma Soil Series while increases of 4 % and 17 % were obtained on Chakunkula soil series. This study demonstrated potential advantages of applying agricultural lime in aqueous suspension compared to applying it in dry powder form but more investigations are needed.

**Key words:** Liming, pH, Exchangeable acidity, Lime formulation, Soya beans, Yield

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## **DEDICATION**

To my beloved late mum, Anerty Chikonde Kambikambi for her unwavering support and unfeigned love of seeing me through the educational system.

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## **ABBREVIATIONS AND ACRONYMS**

AAS	Atomic Absorption Spectroscopy
ANOVA	Analysis of Variance
ATDC	Agriculture Technology Demonstration Centre
CCE	Calcium Carbonate Equivalent
DMRT	Duncan's Multiple Range Test
ECCE	Effective Calcium Carbonate Equivalent
ENV	Effective Neutralising Value
FF	Fineness Factor
KKIA	Kenneth Kaunda International Airport
NV	Neutralizing Value
USDA	United States Department of Agriculture
ZARI	Zambia Agricultural Research Institute

## CHAPTER ONE: INTRODUCTION

### 1.1 Background

Soil acidity is one of the factors that limit crop growth and yield in many parts of the world. The challenges it presents to agricultural productivity in the world especially in the tropics and subtropics of Africa and Latin America are highly recognized (Summer *et al.*, 1991). According to Von Uexküll and Mutert (1995), about 3,950 million hectares of land are classified as having acid soils, where acid soils are defined as soils with surface layers that have pH values lower than 5.5.

In Zambia, soil acidity is prevalent in highly weathered soils, such as the Ultisols and Oxisols that dominate the high rainfall northern region of the country commonly referred to as agro ecological region III (Goma and Singh, 1993). Results of recent studies undertaken on smallholder farms in Zambia indicate that the problem of soil acidity is widespread across all soil types (Yerokun, 2006) and affects all parts of the country and is not confined to the agro ecological region III alone (Mulungwe *et al.*, 2013).

Soil acidity develops as a consequence of a number of processes which are controlled by biological, climatic and anthropogenic factors. Farming practices such as long term continuous use of nitrogen fertilizers such as ammonium nitrate and urea may induce acidity (Lungu and Chinene, 1993). Natural processes associated with weathering of acidic parent rock material cause acidity (McLean, 1971). Bolan *et al.*, (2003) reported that leaching of base cations in the upper soil profile leads to dominance of aluminium ions in the soil which induce the soils to become acid. Furthermore, reactions in the soil such as acid deposition from fossil fuels and acid rainfall from polluted air also lead to acidification of soils.

Soil acidity limits crop productivity by inducing toxicities due to elements such as aluminium (Al) and manganese (Mn) and is also associated with the occurrence of deficiencies of nutrients such as phosphorus (P), calcium (Ca), magnesium (Mg), and molybdenum (Mo). Soil acidity has, therefore, been recognized for many years as a

factor influencing plant growth and this may be due to any of the following components of the acidity complex: (i) low pH (ii) deficiencies of P, Ca and Mo or (iv) greatly increased availability of such elements as Mn and Al to the point of acidity or toxicity (Mayz and Cartwright, 1984). According to Zhenge (2010), Al in acid soils is solubilised into ionic forms when the pH drops below 5. These ionic forms of Al are known to be very toxic to plants. They initially inhibit elongation of roots by destroying the cell structure of the root apex and thus adversely affect water and nutrient uptake by the roots. This results in poor growth and development of plants.

Yerokun (2006) reported that soil acidity increases the potential for heavy metal toxicity to plants. Studies show that soil acidity decreases the activities of microorganisms in soils. Rousk *et al.*, (2010) reported a fourfold decline in the growth and activity of bacteria in soils in the United Kingdom as the pH declined from 8.4 to 4.5, which was accompanied by a fourfold increase in the growth and activity of fungi.

The common management practice used to control problems associated with soil acidity is to apply agricultural lime to affected soils. Agricultural lime is a broad term used for materials applied to the soil to neutralize soil acidity and these include carbonates, oxides and hydroxides of Ca and/or Mg (Shitumbanuma, 2006). The process of applying agricultural lime to acid soils is termed liming. Besides ameliorating soil acidity, agriculture lime adds Ca and Mg to the soil and also immobilizes toxic heavy metals in the soil (Haynes and Naidu, 1998; Bolan *et al.*, 2003). To optimize crop production, acid soils require liming to increase the pH to a desirable range that increases the bioavailability of nutrient elements in the soil and reduces the bioavailability of potentially toxic elements such as Al. Liming also makes the soil environment favourable for microbial activity which is necessary for recycling of nutrients held in soil organic matter.

A review of research results on liming in Zambia by Goma and Singh (1993) showed that liming generally increased crop yields. They further observed that leguminous crops were more likely to respond to liming than cereals and that effects of liming were not always apparent in the first year of application but their effects continued



through the third and fourth years. Despite its positive effect on soil acidity, adoption rates on the utilization of lime in crop production have remained low.

Yerokun (2006) suggested that the lag in crop response to liming was probably a contributing factor to the slow adoption of liming by small scale farmers. Shitumbanuma (2006) reported that often times farmers who needed agriculture lime, especially in rural areas, could not find it readily available. Additionally, Lungu and Chinene (1993) cited lack of access to agricultural lime as another factor that limited the use of lime by smallholder farmers. They further noted that crop response to application of agricultural lime was not as high as that of fertilizers and therefore, smallholder farmers would not readily opt to purchase agricultural lime. Although agricultural lime is generally a low cost bulky product, the high transportation costs make it an unfavourable commodity to deal in by smallholder agro dealers in remote locations. Furthermore, lack of readily available information on the properties and quality of agricultural lime as well as its proper usage, further compounds the problem of its low usage.

Ground calcium carbonate rocks are the common materials used in Zambia as agricultural lime. Recently, some new imported agricultural liming materials sold in aqueous suspension have been introduced on the Zambian market. Vendors of these products claim that the products are more effective in neutralizing soil acidity than the traditional dry powder agricultural lime. Furthermore, it is claimed that 6.25 litres of the aqueous liming material, corresponding to about 3 kg of dry liming material can neutralize soil acidity in a one hectare field. This quantity of agricultural lime appears to be too small compared to common recommended rates of about 200 to 500 kg of dry powder pure  $\text{CaCO}_3$  per ha (Goma and Singh, 1993).

## **1.2 Statement of the Problem**

Soil acidity is a widespread problem in Zambia. Liming is the most common option for correcting this problem among farmers who can access and afford agricultural lime. Agricultural lime is commonly applied to the soil as a dry powder material. New imported agricultural liming materials in aqueous suspension have recently been

introduced on the Zambian market with claims that they are more effective in neutralizing soil acidity than the traditional dry powder forms.

So far there have been no published local studies on the effects of applying agricultural lime in aqueous suspension to acid soils in Zambia. Furthermore, no attempt has been made to establish how applying local agricultural liming materials in aqueous suspension to acid soils would affect their ability to neutralize soil acidity compared to their dry powder forms. If agricultural liming materials are to be utilized effectively, there is need to objectively establish whether their performance is affected by the form in which the materials are applied to acid soils.

### **1.3 Justification**

There is limited information on the suitability and performance of various forms of liming materials available on the Zambian market. The absence of researched data to support the use of liming materials may be a contributing factor to the low usage of agricultural liming materials. Both government and non- governmental organizations are involved in the supply and distribution of agricultural lime. In contrast, very few institutions are involved in establishing the agronomic performance of these materials that are supplied to farmers. It is, therefore, important to establish the quality and performance of agricultural lime products being sold to farmers as soil amendments.

There have been instances, of the misuse of agricultural lime owing to the lack of information on their proper use that has resulted in excessive application of lime which in turn has adversely affected crop growth. Such experiences have led some farmers to completely shun the use of agricultural lime. To avoid such adverse experiences, there is need to properly examine the products being introduced on the market before they are distributed to farmers. Products that are introduced with researched data on their proper usage and performance are likely to be properly used and will contribute to improving crop productivity and incomes of farmers engaged in crop production.

### **1.4 Main Objective of the Study**

The main objective of the study was to evaluate whether the effectiveness of liming materials in neutralizing soil acidity is affected by the form in which it is applied to the soil.

### **1.5 Specific Objectives**

The specific objectives of the study were to:

1. To evaluate the effect of lime application form on soil pH.
2. To evaluate the effect of lime application form on exchangeable soil acidity.
3. To determine the effect of lime application form on the grain yield of soya beans.

### **1.5 Hypotheses**

The hypotheses tested were:

1. Agricultural lime applied in aqueous suspension is more effective in raising the pH of the soil than agricultural lime applied in dry powder form.
2. Agricultural lime applied in aqueous suspension is more effective in reducing the exchangeable acidity of the soil than agricultural lime applied in dry powder form
3. Soya bean grain yields obtained from plots treated with agricultural lime in aqueous suspension are higher than those obtained from plots treated agricultural lime in dry powder form.

### **1.6 Organization of the Dissertation**

This dissertation has five chapters. Chapter 2 presents literature on the state of knowledge related to the subject of this study and the limitations. Chapter 3 describes the location and conditions of study sites, methods used to determine properties of soils and liming materials, the design of laboratory and field studies and methods for statistical analysis used. Chapter 4 presents and discusses the results of the study while Chapter 5 presents the conclusions and recommendations of the study.

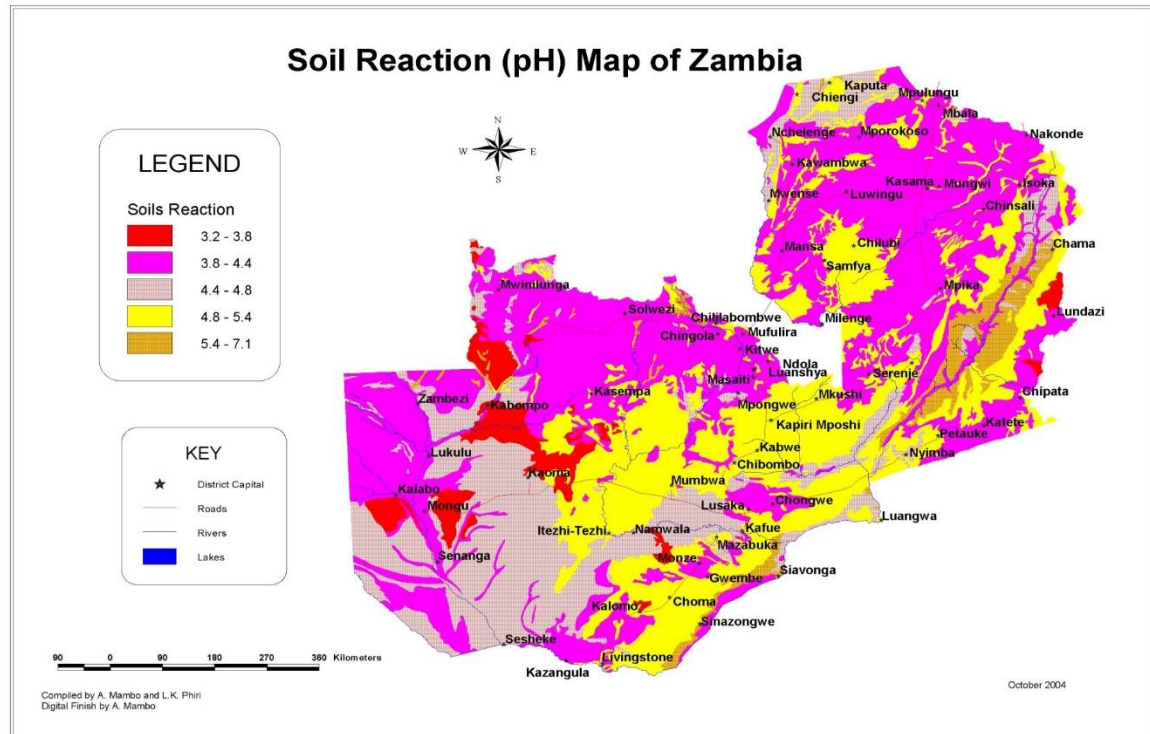
## CHAPTER TWO : LITERATURE REVIEW

### 2.1 Characteristics of Acid Soils in Zambia

Soils with pH values lower than 5 are considered acidic. Soil acidity is characterized by the presence of hydrogen ( $H^+$ ) and aluminium ( $Al^{3+}$ ) ions in soil solution and on the exchange complex (Brady, 1984). Therefore, higher concentrations of  $H^+$  and  $Al^{3+}$  ions in the soil solution are associated with high levels of acidity or low soil pH. According to Hede *et al.*, (2003), levels of soil acidity are influenced by biological activities in the soils and the climatic conditions of the location. Acid soils exhibit low pH and high level of acidic cations ( $H^+$ ,  $Al^{3+}$ ) resulting into Al and Mn toxicities as well as nutrient deficiencies particularly P, Ca, Mg and Mo.

Lungu and Chinene (1993) reported that soil acidity in Zambia is common in the high rainfall region with Oxisols and Ultisols as well as in other intensively cultivated poorly buffered light textured soils. The distribution of soil acidity in Zambia is as shown in Figure 1.

Temperature and rainfall are the two main parameters that have a direct influence on soil development as rainfall provides moisture for most weathering reaction while temperature provides the energy that drives weathering reactions in soil formation (Banda, 2009). Therefore, the levels of acidity in the soil are expected to be high with increasing amounts of precipitation and relatively higher temperature especially in Agro Ecological region III as shown in Figure 2. However, Lungu and Chinene (1993) reported that soil acidity is wide spread and increasing on intensively cultivated soils. Further, Phiri *et al.*, (2006) reported that more than 90 % of the soils analyzed from Chadiza, Chipata and Lundazi district in Eastern Province; Chongwe, Chibombo and Lusaka district in Lusaka Province; Mazabuka, Monze and Gwembe districts in Southern Province were acid, exhibiting low soil pH values ranging from 4.5 to 6.0 across all soil types. These are the major agricultural production areas in the country.



Source: Mambo and Phiri (2003).

Figure1: Soil acidity Map of Zambia.

Acid conditions are not favourable for crop growth especially on crops which are sensitive to acid soils such as legumes. Studies conducted by Fageria and Baligar (2003) have shown that when Al is in abundance, P is fixed as insoluble aluminium phosphate, making it unavailable for plant uptake. When the pH increases, most micro nutrients are in their bioavailable forms in the soil except Mo and they may become toxic in excessive quantities since these are required in minute amounts. Nutrient deficiencies due to acid conditions lead to poor crop growth and poor yields. This is one of the major crop production challenges facing farmers in Zambia especially smallholder farmers.

## 2.2 Causes of Soil Acidity

Soil acidity is caused by a number of processes that cause excessive release and accumulation of  $Al^{3+}$  and  $H^{+}$  ions from the soil or sediments from the processes of

weathering of rocks. Consequently, any reaction in the soil that results in the release of these ions causes soil acidity. The acidification process can either be through a natural process or induced by anthropogenic interventions. In Zambia, soil acidity is caused through the following processes: weathering of soil parent materials, application of inorganic nitrogenous fertilizers, leaching of bases and accumulation of  $\text{Fe}^{3+}$ ,  $\text{H}^+$  and  $\text{Al}^{3+}$  ions or even a combination of these factors.

### **2.2.1 Weathering of Soil Parent Materials**

The process of weathering of basic rocks and minerals results in the release of basic cations which are eventually replaced by acidic cations ( $\text{H}^+$  and  $\text{Al}^{3+}$ ) on the soil exchange complex. Further, Hede *et al.*, (2003) reported that soils that develop from granite parent materials acidify at a faster rate than soils developed from calcareous parent materials. He further observed that sandy soils with relatively small amount of clay acidify more rapidly due to their smaller reservoir of alkaline cations and higher leaching potential. The chemical composition of the parent rock material may change over time due to a number of factors in the environment such as precipitation due to climate change. Consequently, soils that may develop from materials such as granite are expected to be more acidic than those from calcareous parent materials leading to soil acidification.

### **2.2.2 Leaching of Cations**

Goma and Singh (1993) reported that soil acidity in Zambia was initially identified in high rainfall regions of agro ecological region III because of the effect of heavy rainfall in leaching base cations in the upper soil profile. The leached base cations lead to predominance of aluminium ions on the soil exchange complex.

Some cations are removed from the soil through harvesting of crops and this contributes to soil acidity development. The roots of high-yielding grain and forage crops remove basic cations from the soil and release hydrogen into the soil solution to maintain an ionic charge balance within the tissue. The removal of crop residues which are rich in basic cations from the field is also responsible for development of

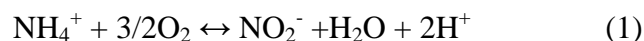
acidity. In this way, soil acidity develops faster in continuous cropping with high plant biomass than those with high grain yield (Van der Pol, 1992). The removal of basic cations lead to reduced base saturation and low pH as basic cations are replaced by acidic cations such as  $\text{Al}^{3+}$  and  $\text{H}^+$  ion.

### **2.2.3 Decomposition of Organic Matter**

Decomposition of organic matter in the soil releases hydrogen ion ( $\text{H}^+$ ) which contributes to development of acidity. This is caused by the release of carbon dioxide through the process of decomposition which reacts with water to form a weak acid, carbonic acid and other weak organic acids are also produced from this process. Mineral soil containing large amounts of organic matter and organic acids contribute significantly to soil acidity (Havlin *et al.*, 2005). Additionally, plant roots absorb cations from the soil and release hydrogen ions to balance on the charge and when these hydrogen ions accumulate in the soil, they cause soil acidity. The respiration of plants releases carbon dioxide in the soil which reacts with water to form a weak carbonic acid ( $\text{H}_2\text{CO}_3$ ). This contributes to development of soil acidity.

### **2.2.4 Ammonia Fertilizer**

Lungu and Chinene (1993) asserted that the most widely used fertilizers in Zambia are Compound NPK, urea and ammonium nitrate. The negative effects of long term use of fertilizers especially those high in nitrogen such as urea and ammonium nitrate are well documented. Research and subjective experience of farmers all attribute observed declining yields to the use of these fertilizers. There is no doubt that soil acidity limits crop production under continuous cultivation if agricultural lime is not applied. The inadequate supply of lime in Zambia due to non exploitation of existing lime deposits is exacerbating this situation. In some cases, this has led to abandonment of agricultural land. Soil acidity resulting from continued applications of fertilizers is due to the nitrification process in the soil. The microbial oxidation of ammonium ions generates hydrogen ions which directly cause soil acidity. This process is represented by equation 1:



For every ammonium ion, two hydrogen protons are generated. The production of hydrogen protons during nitrification is the basis for recommendations to maintain liming programmes with use of fertilizers. From the above reaction, one calculates that 1 kg of ammonium nitrogen will generate acidity that requires 3.6 kg of  $\text{CaCO}_3$  or 2 kg of  $\text{CaO}$  to neutralize (Lungu and Chinene, 1993).

Lungu and Dynoodt (2008) reported that nitrification occurs rapidly in most soils. During this process, a window of opportunity for ammonium ion plays a role in soil acidity process and theoretically, two moles of hydrogen ion are released per mole of ammonium ion converted to nitrate. The amount of nitrogenous fertilizer applied on most Zambian soils varies according to farming system (Lungu and Chinene, 1993). This is the source of soil acidity in highly cultivated soils without proper liming programmes. Lastly, a study by Lungu and Dynoodt (2008) demonstrated that long term application of urea resulted in soil acidification and decrease in exchangeable bases such as Ca and Mg in the soil.

### **2.3 Effects of Soil Acidity on Plant Growth**

Soil acidity is a property that influences soil fertility through the availability of nutrients and is therefore linked to low productivity (Lungu and Dynoodt, 2008). Soil acidity is related to the pH of the soil which is a measure of the acidity or alkalinity of the soil. This property has negative effect on plant growth by affecting plant nutrient availability and the resulting plant growth. According to Nyarko (2012), two fundamental factors associated with acid soil infertility are nutrient deficiencies such as P, Ca and Mg and the presence of phytotoxic substances such as soluble Al and Mn when present in higher concentrations.

Nutrients needed in large amounts by plants are referred to as macronutrients and include nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S). Elements that plants need in trace amounts are called trace nutrients or micronutrients. Trace nutrients are not major components of plant tissue but are



essential for growth. They include iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), cobalt (Co), molybdenum (Mo), and boron (B). The availability of nutrients is influenced by the pH of the soil.

Soil pH affects nutrient balance of both macro and micro nutrients. In slightly moderate alkaline soils, Mo and macronutrients (except for P) availability is increased but P, Fe, Mn, Zn Cu, and Co levels are reduced and may adversely affect plant growth. In acidic soils, micronutrient availability (except for Mo and B) is increased. Nitrogen is supplied as ammonium ( $\text{NH}_4^+$ ) or nitrate ( $\text{NO}_3^-$ ) in fertilizer amendments and dissolved N will have the highest concentrations in soil with pH 6 to 8. Concentrations of available N are less sensitive to pH than concentration of available P. In order for P to be available to plants, soil pH needs to be in the range 6.0 and 7.5. If pH is lower than 6, P starts forming insoluble compounds with Fe and Al and if pH is higher than 7.5, P starts forming insoluble compounds with Ca. Most nutrient deficiencies can be corrected between the pH ranges of 5.5 to 6.5 provided that mineral soils and organic matter contain the essential nutrients. Yost (2000) observed that soil fertility declines because of the detrimental effect of the toxicities of Al and Mn through reduced root proliferation and function and the unavailability of essential nutrients such as P, Ca, Mg and Mo. Further, Langer *et al.*, (2009) observed that  $\text{pH} \leq 5.5$ , Al toxicity is the main stress factor to plant growth and limits plant growth while Tabuchi and Matsumoto (2001) reported that aluminium in excess harms the crop by inhibiting or stopping root growth as a result of Al toxicity leading to stunted growth.

Soil acidity has a great effect on the solubility of nutrients and limits crop productivity by inhibiting the solubility of essential plant nutrients (Sumner *et al.*, 1991). Soil acidity is distinguished by its low pH and abundant cations such as H, Mn, Fe and Al on system colloidal soil solution. Mattiello *et al.*, (2010) reported that high levels of  $\text{Al}^{3+}$  and  $\text{Mn}^{2+}$  ions are toxic to plant growth but Al toxicity is considered as the main factor limiting crop growth in acid soils. Nyarko (2012) reported that plants absorb nutrients mainly in soluble forms in the soil but under acidic conditions; some of the vital nutrients such as P, Ca and Mg are made unavailable in the soil solution for plant

uptake due to the excessive presence of elements such as Al and Mn. He further reported that the principal effects on plant growth from soluble aluminium in the soil solution is increased acidity via Al hydrolysis and reduced root growth and function, which is generally observed in the roots in the field as stunted and club shaped. This reduces the ability of plants to extract water and other nutrients in the soil. Consequently, the plants will not grow or produce to their full potential. Research in Zambia has also demonstrated that soil acidity increases the potential for heavy metal toxicity to plants (Yerokun, 2006).

Soil acidity has considerable influence on plant growth by its effect on the activity of beneficial microorganisms in the soil. Soil acidity is known to decrease the activities of soil microbes (McCauley *et al.*, 2017). Bacteria that decompose soil organic matter are hindered in strongly acidic soils (Rousk *et al.*, 2010). This prevents organic matter from breaking down, resulting in an accumulation of organic matter and the tie up of nutrients, particularly nitrogen, that are held in the organic matter. Helyar and Porter (1989) observed that decomposition of soil organic matter ceases when Al content is high in the soil with pH less than 4.5. Therefore, low acidity hinders microbially mediated processes.

## **2.4 Liming**

Liming is the application of lime to acid soil. Agricultural lime is a broad term applied to oxides, hydroxides, carbonates and silicates of Ca and Mg that neutralizes soil acidity (Shitumbanuma, 2006).

### **2.4.1 Types of Liming Materials**

Liming materials vary in their mineralogical composition, neutralizing capacities and their reactivity. Liming materials can be categorized as stated below based on these and other factors including the following:

- i) Dolomitic Lime. This is ground limestone comprising calcium and magnesium known as dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ). According to Peters *et al.*, (1996), dolomitic

limestone reacts more slowly with acidic soils than calcitic lime and may have Calcium Carbonate Equivalent (CCE) higher than 100 percent depending on the purity of the material. The application of dolomitic lime adds magnesium and calcium to soils deficient in these mineral elements.

ii) Calcitic Lime. This is ground limestone comprising calcium carbonate ( $\text{CaCO}_3$ ). Ground limestone usually contains  $\text{CaCO}_3$  and some impurities. However, some limestones will also include  $\text{MgCO}_3$ . Ground limestone with less than 1- 6 % Mg is called “calcitic limestone”. If the limestone has 6 % Mg or more, it is designated “Dolomitic Limestone”. According to Carey *et al.*, (2006), pure calcite is used as the standard when measuring the acid-neutralizing values of all other liming materials.

iii) Hydrated lime is calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ). It is a very fast - acting powdery lime material which is caustic and can easily burn plants that are already established. Finely ground hydrated lime can have ENV's of 120 - 135%. If too much of this material is applied, the soil pH could quickly rise beyond the targeted level.

iv) Burned lime or ‘Quick lime’ is ground limestone that has been burnt at high temperatures to remove carbon dioxide and leave calcium oxide ( $\text{CaO}$ ). Pure calcium oxide has a CCE of 178 % and reacts quickly. Magnesium oxide ( $\text{MgO}$ ) may also be present if  $\text{MgCO}_3$  were present in the ground limestone. Burned lime needs to be handled carefully as it quickly reacts with water to form hydrated lime and releases large amounts of heat (Carey *et al.*, 2006).

v) Fluid Lime. This is a term generally used to describe finely grounded limestone suspended in water at a ratio of about 50% water to 50% limestone. Producers of fluid lime usually utilize finely ground limestone which passes a 200 mesh screen with high neutralizing values. However, some fluid lime contains 48% limestone, 2% clay as a dispersant and 50 % water. Fluid lime is able to change soil pH in a relatively shorter period of time and this presents its distinct advantage in situation where low pH was discovered after planting.

Liming material is traditionally applied in powder but can also be applied as a suspension. The form in which lime is applied to acid soils depends on the objective of the user. Lime in powder has residue effect and takes slightly longer to react completely compared to suspension form. The application of lime in suspension has been suggested for cropping situation where fast reaction is recommended such as no till and application rates are much lower than those in convectional dry lime (Peters *et al*, 1996). The other aspect is the cost of lime. The cost of dry lime application should be compared to the cost liquid lime applications if one want to derive maximum benefits at minimum cost. Generally, liquid lime costs more compared to dry powder lime.

#### **2.4.2 Quality Parameters of Liming Materials**

The suitability of a material intended for use in ameliorating soil acidity is determined by a number of factors, which include; the neutralizing value of the materials, the particle size distribution and the chemical reactivity of the material besides other factors such as moisture content, hardness of the rock ((Peters *et al*.,1996; Shitumbanuma, 2006)).

Liming material can be applied to the soil to ameliorate soil acidity either in dry powder form or in aqueous suspension to the soil. Lime in aqueous suspension react quickly and bring about rapid increase in soil pH, but have limited residual effect for maintaining soil pH. One drawback may be that the total amount of lime that can be applied is usually less than with dry limestone. Thus, more frequent lime applications are needed. These materials also tend to be more expensive than dry agricultural lime (Bast *et al*., 2011).

#### **2.4.3 Neutralizing Value**

The ability of a liming material to neutralize acid is determined by the amount of acid it is able to neutralize compared to the quantity of acid that the same mass of pure calcium carbonate ( $\text{CaCO}_3$ ) is able to neutralize. The liming material's capacity to neutralize acid is expressed as a percentage of the capacity of pure  $\text{CaCO}_3$  to

neutralize acid and is called calcium carbonate equivalence (CCE) or NV of the material (Shitumbanuma, 2006). The lower the neutralizing value of a liming material, the greater the amount required to neutralize soil acidity. Liming materials usually contain other materials that do not neutralize acidity. The presence of such materials reduces the CCE of the liming material compared to pure materials (Carey *et al.*, 2006). Table 1 shows the CCE of the major mineral constituents of common liming materials.

Table 1. Composition of Major Constituents of Liming Materials

Name of Constituent	Chemical formula	CCE	Liming Materials
Calcite	$\text{CaCO}_3$	100	Calcitic Lime
Dolomite	$\text{CaMg}(\text{CO}_3)_2$	109	Dolomitic Lime
Lime	$\text{CaO}$	179	Quick Lime
Portlandite	$\text{Ca}(\text{OH})_2$	136	Hydrated Lime

Adapted from (Tucker, 1988).

#### 2.4.4 Particle Size Distribution

The particle size of agricultural lime has an influence on the rate at which lime reacts with moisture when incorporated in the soil. Smaller particles have a larger surface area per unit mass exposed for reaction with acid. They, therefore, react faster than coarse grained materials (Shitumbanuma, 2006). According to Carey *et al.*, (2006), the rate of reaction of a liming material is determined by their particle size. All particles passing through a 100-mesh screen react within the first year of application while only 60 % of particles passing a 20-mesh sieve (but held on 100 mesh sieve) react within a year of application. Materials that do not pass through a 20 mesh sieve usually are not expected to react within a year following their application.

#### **2.4.5 Effective Neutralizing Value**

The particle size and neutralizing value are used together to determine the overall quality of lime. For practical purposes the CCE has to be adjusted for the fineness of the material to determine the ENV or ECCE. The ENV is obtained by multiplying the NV of the liming material and the degree of fineness of the material. Barber (1984) and Tisdale *et al.*, (1985) describe in detail the procedure for calculating the ENV. The ENV is calculated from equation 2:

$$\text{ENV} = \text{NV} * \text{FF} \quad (2)$$

where: FF = Fineness factor expressed as decimal between 0 and 1; and NV = Neutralizing Value.

#### **2.4.6 Chemical Reactivity**

The rate at which soil acidity is neutralized by agricultural lime depends on the mineralogical composition of the liming material. Chemical reactivity is influenced by the type of minerals present in the liming material. Barber (1984) noted that the relative amount of calcite and dolomite and the fineness of the particles greatly influence the chemical reactivity of liming materials. Study results by Kapembwa (2014) have shown that dolomitic limestone reacts more slowly than calcitic limestone all other factors being equal.

#### **2.4.7 Other Factors**

A number of factors besides the ones stated above determine the suitability of a liming material. According to Jones (1979), these factors include moisture content of the liming material and the hardness of the carbonate rock. Shitumbanuma (2006) also cites the ratio of magnesium to calcium in the lime and the presence of other elements that may be beneficial or harmful to the plant also as factors that determine the suitability of liming materials.

## **2.5 Effects of Liming on Acid Soils and Soya bean Yield**

### **2.5.1 Soil Acidity**

Soil exchangeable Al is a factor considered when deciding whether or not to apply lime to a soil. When the pH is less than 5.0, the application of lime to the soil is generally recommended. This may be either to raise the pH to some desired level suitable for optimal crop growth or to reduce the levels of soluble aluminium. Liming acid soils changes the chemical condition of the soil. Some of the benefits of liming the soil include: (i) reducing the level of soil acidity (ii) making nutrients such as P, Mo and B more soluble and available to plant (iii) creating a favourable conditions for microbial mediated processes such as N fixation (iv) supplying Ca and Mg to the soil depending on the type of lime applied (v) improving soil structure.

### **2.5.2 Soya Bean Yield on Acid Soils**

Research on the application of lime to acidic soils has shown that liming tends to improve Soya bean yields. A study by Anetor and Akinrinde (2006) in Nigeria showed that applying lime increased root and shoot yields of soya beans. Okpara *et al.*, (2007) reported a 66 % increase in Soya bean yield compared to the control after applying 1000 kg lime /ha. Swallow *et al.*, (2011) reported a 32 % increase in soya bean yield in the USA after applying 5 metric tons lime /ha. Bekere (2013) in Ethiopia also reported significant improvement of growth of soya beans grown on acid soils after applying lime. A study by Kumar *et al.*, (2012) showed a yield increases in soya bean of 32 % compared to the control after applying lime at a rate 300 kg/ha in furrows.

In Zambia, research results show that lime applied at rates lower than 2 ton/ha broadcast across fields and at rates of 100 - 500 kg ha<sup>-1</sup> in fields with planting basins plots can be profitable in maize, soya bean and groundnut production and even be more profitable with marginal returns of more than 150% if this is combined with compost (Mulungwe *et al.*, 2013). However, a review of studies on the effect of liming in Zambia by Goma and Singh (1993) showed that the benefits of liming vary with the type of soil and are not as consistent as those of applying chemical fertilizer. Results

of a study on Konkola soil series with exchangeable  $\text{Al}^{3+}$  content of  $1.1 \text{ cmol kg}^{-1}$  soil showed that Soya bean responded significantly ( $p < 0.05$ ) to lime application and yields increased with increasing rates of lime up to  $2,000 \text{ kg ha}^{-1}$ . On the other hand, results of a study on Maheba soil series that was also acid showed no significant response to liming in the first year although the exchangeable  $\text{Al}^{3+}$  content in the soil was  $1.4 \text{ cmol (+) kg}^{-1}$ . On Mufulira and Misamfu Yellow soil series, no significant soya bean response to liming was observed. Further, Lungu and Chinene (1993), in their review of the results of nation-wide lime trials, concluded that liming did not seem to increase crop yields to anywhere near to or even to half the potential yield of crops or to yields obtainable in favourable non-acid areas. McKenzie *et al.*, (2008) reported increased yield in Al sensitive wheat cultivars when lime was applied to acid soils in Northern Province of Zambia. Based on these results, it was concluded that crop response to liming also depended on the cultivar that was grown. Acid or Al sensitive cultivars were more likely to respond to liming than non Al sensitive cultivars. Nwachuka (2008) showed that the magnitude of yield in response to liming depends on the level of Al in the soil with high responses expected from soil with high levels of Al saturation and with lower or no response from soil with low levels of aluminium saturation.

The studies conducted on agriculture lime as alluded to earlier have focused on the application of lime in powder form and its effect in ameliorating soil acidity. Additionally, there have been limited information and little or no published local studies on the effects of applying agricultural lime in aqueous suspension to acid soils in Zambia. Newly introduced lime in aqueous suspension on the Zambian market has not been tested to establish how applying local agricultural liming materials in aqueous suspension to acid soils would affect their ability to neutralize soil acidity compared to their dry powder forms. The focus of this research was therefore to assess the potential advantages of apply lime in aqueous suspension as opposed to the dry powder form.



## CHAPTER THREE : MATERIALS AND METHODS

### 3.1 Location of Study Sites

This study involved laboratory and field studies. The laboratory study was carried out at the School of Agricultural Sciences at the Great East Road Campus of the University of Zambia in Lusaka. Field studies involved crop trials which were conducted at two sites. The first site was at Liempe Farm located at latitude 15° 23' 13.2'' South and longitude 28° 29' 13.2'' East and elevation 1160 m above sea level and the second at Agriculture Technology Demonstration Centre (ATDC) located at 15° 21' 25.2'' South and longitude 28° 27' 25.2'' East at an elevation of 1149 m above sea level, both in Chongwe District of Lusaka Province of Zambia as shown in Figure 2. Agro-ecological region IIa is characterised by mean annual rainfall of 800 to 1000 mm.

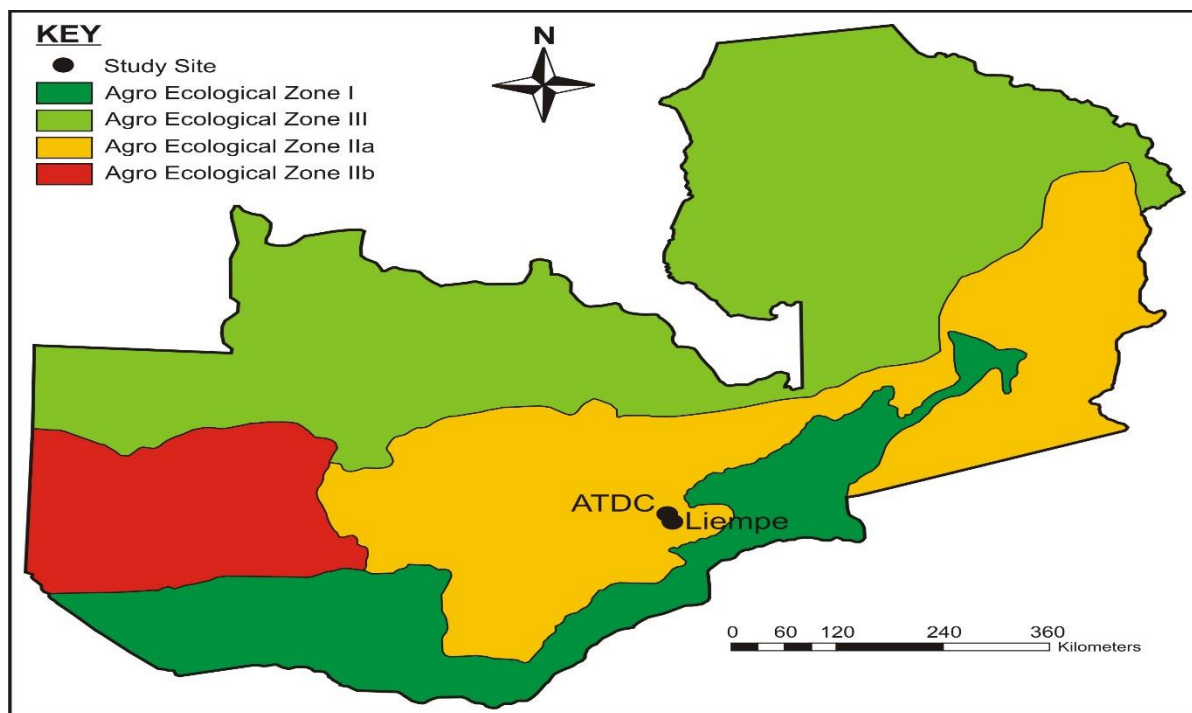


Figure 2: Agro-ecological zone map of Zambia showing location of study sites.

### **3.2 Soil and Climatic Conditions**

#### **3.2.1 Soil**

The soils at the site used for field trials at Liempe Farm were classified in USDA Soil Taxonomy as Fine Mixed Isohyperthermic Typic Kandistalfs belonging to Chakunkula Soil Series while the soil at the ATDC were classified as Fine Loamy, Mixed Isohyperthermic Typic Kandistalfs, belonging to Choma Soil Series (Magai, 1985). The soils at the two sites are moderately weathered and moderately leached with medium to strong acidity derived from inherently acidic rocks which are low in basic cations. Consequently, the experimental sites were chosen in this region because of the limitation of soil acidity to crop production.

#### **3.2.2 Climate**

The general climate of the two study sites is typical of the climate of most of the plateau region of Zambia. It is described as being a moderate tropical continental climate with three distinct seasons. According to Muchinda and Spaargaren (1985), the three distinct seasons of Zambia include a cool and dry season from April to August, a hot to dry season from September to October and a warm and wet season from November to March.

The two study sites are located in Agro-Ecological Zones II of Zambia, which is characterized by a mean annual rainfall range of 800 to 1000 mm. The long term climatic data for the nearest meteorological station of the two study sites – Kenneth Kaunda International Airport (KKIA) are presented in Table 2.

Based on the long term climatic data presented in Table 2, the long term mean annual air temperature was calculated as 19.4 °C. The rainy season which starts from October and ends in April is the main crop growing season for rainfed crops and has a mean air temperature of 22.5 °C. Temperatures in the rainy season are, therefore, not limiting for the production of field crops such as soya bean, which was the test crop in this study.

Table 2. Long Term Climatic Data

Month	Rainfall (mm)	T min (°C)	T max (°C)	Day	Sunshine	PET (mm)
				Length (Hrs)	Hrs (Hrs)	
January	247.71	17.61	27.09	12:53	5:32	105.10
February	185.73	17.40	27.31	12:33	5:59	93.18
March	104.05	16.39	27.57	12:10	7:01	113.59
April	30.11	13.99	27.19	11:44	8:52	115.59
May	0.4	10.65	25.58	11:23	8:50	111.30
June	0.0	7.76	23.76	11:12	9:07	97.37
July	3.37	7.14	23.94	11:17	9:26	107.00
August	2.18	9.16	26.63	11:34	9:49	130.21
September	0.0	12.84	30.12	11:73	9:41	173.07
October	18.82	16.05	31.65	12:25	8:55	188.10
November	94.89	17.41	30.25	12:47	7:37	145.11
December	201.5	17.63	27.79	12:56	5:44	117.09
	883.21	13.67	25.11	12.01	8.03	124.7

Source: Based on data from Kenneth Kaunda International Airport (KKIA).

### 3.3 Site Selection and Sampling of Soils

In this study, the sites of interest were locations with arable land that had acid soils that required liming. Therefore, when selecting crop trial sites, the main criterion was the availability of arable land with soils exhibiting pH values of lower than 4.5 as measured in 0.01M CaCl<sub>2</sub>. To assist with identifying suitable sites, field pH indicator kits were used to test the pH of the soils in the fields. Suitable sites were identified and secured at Liempe Farm and at the ATDC.

At each site, surface samples from 0 - 20 cm depth were randomly collected from each field using a spade. Simple random sampling was used. Subsamples collected from the fields were mixed in clean plastic buckets to make large composite samples. About 2 kg of the composite samples were collected for laboratory analysis. A further 50 kg of

soil sample was collected from each site for use in laboratory incubation studies to determine the effect of the form of the liming materials on soil pH and exchangeable acidity. Core rings were used to collect undisturbed soil samples for determining bulk density of the soil. Samples for determining bulk density were collected in triplicate. The core ring samples were also taken for laboratory analysis.

### **3.4 Laboratory Analysis**

#### **3.4.1 Sample Preparation**

Composite samples obtained from the field were air dried, disaggregated and passed through a 2.0 mm sieve. The portion of the soil passing through the 2 mm sieve was retained for further analyses. The soil properties determined include; pH, exchangeable acidity, exchangeable bases, organic carbon content, particle size distribution, available P and total nitrogen. All laboratory analyses of the soil properties were carried out in quadruplicate.

#### **3.4.2 Soil pH**

To determine the pH of the soils, 10 g samples of sieved air dry soil was placed in a 50 mL beaker to which 25 mL of 0.01M  $\text{CaCl}_2$  was added. The soil suspension was shaken for 30 minutes and then allowed to settle for 10 minutes. The pH was measured in the supernatant using a pH electrode, initially calibrated with standard pH reference solutions at pH 4 and 7. The pH readings of each sample were recorded.

#### **3.4.3 Exchangeable Acidity**

To determine the exchangeable acidity of the soil, 10 g samples of soils was weighed and placed in 250 mL Erlenmeyer conical flasks. A 100 mL of 1N KCl solution was added to the flasks, which were then covered with parafilm. The soil suspensions were shaken for an hour and then filtered. A 25 mL aliquot was pipetted into a 250 mL conical flask to which 100 mL of distilled water was added.

Five drops of phenolphthalein indicator was added to this filtrate which was then titrated with 0.01M NaOH till a permanent pink colour was observed. The volume of NaOH

used in the titration was recorded and used to calculate the amount of exchangeable acidity. The amount of exchangeable acidity was determined using equation 3:

$$\text{Exch acidity} \left( \frac{\text{cmol}}{\text{kg}} \right) = \frac{N \left( \frac{\text{eq}}{\text{L}} \right) * \text{Volume NaOH used (L)}}{\text{mass soil (g)}} * 10^2 \left( \frac{\text{cmol}}{\text{eq}} \right) * \frac{1000 \text{g}}{\text{kg}} \quad (3)$$

Where: N= normality of NaOH in titration in eq/L.

To determine exchangeable  $\text{Al}^{3+}$ , 10 mL of 1N sodium fluoride (NaF) solution was added to the filtrate in the flask that had just been titrated with NaOH. The resulting mixture was then titrated with 0.01N HCl until the pink colour of the solution disappeared to form a colourless solution. The volume of HCl consumed in this titration was used to calculate the amount of exchangeable  $\text{Al}^{3+}$  present in the soil. The amount of exchangeable acidity was determined using equation 4:

$$\text{Exch H}^+ \left( \frac{\text{cmol}}{\text{kgsoil}} \right) = \frac{N \left( \frac{\text{eq}}{\text{L}} \right) * \text{Volume HCl used (L)}}{\text{mass soil (g)}} * 10^2 \left( \frac{\text{cmol}}{\text{eq}} \right) * \frac{1000 \text{g}}{\text{kg}} \quad (4)$$

where: N= normality of HCl used in titration in eq/L.

#### 3.4.4 Exchangeable Bases (Ca, Mg, K and Na)

The exchangeable bases were extracted using 1N ammonium acetate ( $\text{NH}_4\text{OAc}$ ) buffered at pH 7.0 from 10 g samples of air dry soils. Fifty millilitres of 1N  $\text{NH}_4\text{OAc}$  solution was added to 100 mL plastic bottles containing 10 g of soil. The suspensions were shaken for 30 minutes and filtered. Concentrations of K and Na in the filtrate were measured by AAS using the Flame emission mode.

A 1 mL aliquot of the filtrate was placed in a 25 mL volumetric flask to which 5 mL of a 5000 ppm solution of  $\text{SrCl}_2$  was added. The mixture was filled to the 25 mL mark with 1N  $\text{NH}_4\text{OAc}$  solution. Concentrations of Ca and Mg were then measured in this solution by AAS on a Perkin Elmer Analyst 400 Spectrophotometer. The concentrations of Ca and Mg in the soil from concentrations in the solution were determined using equation 5:

$$\frac{\text{cmol}(+) \text{ cation}}{\text{kg soil}} = \frac{(\text{Conc cation}(\frac{\text{mg}}{\text{L}}) * \text{Volume of Extract(L)} * \text{DF})}{\text{weight of soil(kg)} * \text{Equivalent weight of cation}(\frac{\text{mg cation}}{\text{cmol}(+)})} \quad (5)$$

where: DF= Dilution Factor.

### 3.4.5 Effective Cation Exchange Capacity (ECEC)

The ECEC was calculated as the sum of exchangeable bases and exchangeable acidity using equation 6.

$$\text{ECEC} \left( \frac{\text{cmol}(+)}{\text{kg soil}} \right) = [\text{Sum of exch bases} + \text{exch Acidity}] \left( \frac{\text{cmol}(+)}{\text{kg soil}} \right) \quad (6)$$

### 3.4.6 Plant Available Phosphorus

Plant available phosphorus in soils was extracted using the Bray 1 method. Three grams of soil was placed in a 50 mL plastic bottle to which 21 mL of the Bray 1 extracting solution was added. The soil suspension was shaken for 1 minute on a mechanical shaker and filtered. A 5 mL aliquot of the filtrate was pipetted into 25 mL volumetric flask to which 4 mL of a solution of freshly prepared colour - developing reagent consisting of a mixture of ammonium molybdate, potassium antimony tartrate, sulphuric acid and ascorbic acid were added. The volumetric flask was filled to the mark with distilled water. The blue colour of the mixture was allowed to develop for about after 15 minutes and the concentration of P in the solution was measured on a UV-Visible spectrophotometer at a wavelength of 882 nm after calibrating the instrument with standards solutions with P concentrations of 0 and 1.0 mg/L. The concentrations of available P in the soils were calculated from P concentrations in the solution using equation 7:

$$\text{P in Soil} \left( \frac{\text{mg}}{\text{kg}} \right) = \frac{\text{P Conc}(\frac{\text{mg}}{\text{L}}) * \text{Volume of extract(L)} * \text{DF}}{\text{mass of soil(g)}} \times 1000 \left( \frac{\text{g}}{\text{kg}} \right) \quad (7)$$

where: DF= Dilution Factor.

### 3.4.6 Total Nitrogen

The Kjeldahl method was used to determine the total nitrogen content of the soil. One gram of soil was weighed and placed in a 50 mL plastic beaker which was thereafter transferred into a test tube to which 4 g of the catalyst mixture (potassium sulphate and anhydrous copper sulphate and selenium powder) was added. Thereafter, 10 mL of the concentrated sulphuric acid ( $\text{H}_2\text{SO}_4$ ) was added to the mixture. The test tubes were covered and heated for two hours on a hot plate to digest the sample. The digest was subsequently removed from the heater and cooled for 30 minutes and later transferred into 100 mL volumetric flask and filled to the mark with distilled water. Thereafter, 10 mL of 10 M sodium hydroxide ( $\text{NaOH}$ ) was added into the distillatory and the receiver was 100 mL conical flask containing 15 mL Boric acid ( $\text{H}_3\text{BO}_3$ ) indicator solution. The distillate was collected for about five minutes and titrated against 0.01N  $\text{HCl}$ . The amount of 0.01  $\text{HCl}$  consumed in this titration is equivalent to the nitrogen in the aliquot taken. The percentage of total N was calculated using equation eight below:

$$\% \text{ N} = \frac{M(\text{HCl}) \left( \frac{\text{mol}}{\text{L}} \right) * (\text{Vol.Sample} - \text{Vol.Blank}) \text{L} * \left( \frac{14 \text{ g N}}{\text{mol}} \right)}{\text{mass of oven dry sample (g)}} * 100 \quad (8)$$

where: DF= Dilution Factor,  $V_s$  = Titre, mL standard acid sample,  $V_s$  = Titre, mL standard acid for blank.

### 3.4.7 Organic Carbon

The Walkley and Black method was used to determine the organic carbon content of the soils. One gram of dry fine earth fraction of the soil sample was weighed in quadruple and put into 250 mL conical flasks. Then, 10 mL of 1N potassium dichromate was pipetted and added to the conical flasks containing the soil sample to which 20 mL concentrated sulphuric acid was added under the fume hood using an automatic pipette. The mixture was swirled gently until the suspension was thoroughly mixed. The suspension was heated on a hot plate in the fume hood for about 30 minutes till the entire sample was completely digested. Thereafter, 150 ml distilled

water and 10 mL phosphoric acid was added to the digested suspension to which ten drops of phenolphthalein indicator was added. Then, 1N ferrous sulphate was titrated against the digested sample till a permanent green end point colour was visible. A blank titration was also conducted to standardize the  $\text{Cr}_2\text{O}_7$  solution. The volume of  $\text{FeSO}_4$  consumed in the titration was recorded. The percent of carbon (% C) was calculated using equation nine as follows:

$$\% \text{ Org C} = \frac{4\left(\frac{\text{g C}}{\text{eq}}\right) \times \left[N\left(\frac{\text{eq}}{\text{L}}\right) \times (\text{Vol blank} - \text{Volume sample}) \text{ mL}\right] \times 10^{-3} \text{ L/mL}}{\text{Mass of soil (g)}} \times 100 \quad (9)$$

where: Vol blank = Volume  $\text{FeSO}_4$  used for the blank, Volume sample = Volume of  $\text{FeSO}_4$  used for the sample), N = Normality of  $\text{FeSO}_4$ .

The percentage of organic matter (OM) was calculated from the Organic C content using equation 10:

$$\% \text{ OM} = \% \text{ Org C} \times 2 \quad (10)$$

### 3.4.8 Micronutrients (Fe, Cu, and Mn)

To determine concentrations of Fe, Cu, and Mn in the soil, 20 g of air dried fine earth (< 2 mm) fraction was weighed into a 125 mL Erlenmeyer flask and 40 mL of diethylenetriamine pent acetic acid-triethanolamine (DTPA-TEA) extraction solution buffered at pH 7.3 was added. The suspension was shaken for 2 hours on the mechanical shaker. The suspension was filtered using Whitman Number 42 filter paper. Concentrations of Fe, Cu, and Mn in the filtrate were determined by Atomic Absorption Spectroscopy (AAS) on a Perkin Elmer Analyst 400 Spectrophotometer. Concentrations of the elements in the soil were calculated using equation 11:

$$\frac{\text{mg Element}}{\text{kg soil}} = \frac{\text{Conc element} \left(\frac{\text{mg}}{\text{L}}\right) \times \text{Volume of Extractant (L)} \times \text{DF}}{\text{Mass of soil (kg)}} \quad (11)$$

where: DF= Dilution Factor



### **3.4.9 Particle Size Analysis**

To determine the particle size distribution of the fine earth fraction, 50 g of the soil sample was weighed and placed in a dispersing cup to which 50 mL of calgon solution was added as dispersing agent. The dispersing cup was filled to half its capacity with distilled water and stirred continuously for 15 minutes. The suspension was then transferred to a 1 dm<sup>3</sup> sedimentation cylinder and filled to the mark with distilled water. The suspension was mixed with the plunger. After thoroughly mixing the suspension, the plunger was carefully removed and the hydrometer was inserted in the cylinder. The hydrometer reading was taken at 40 seconds to determine the percentage of sand in the sample. This was repeated four times to improve the accuracy of the reading. After final 40-second reading, hydrometer was removed and a thermometer was carefully lower into the suspension and the temperature (°C) was recorded. Temperature and hydrometer readings after 2 hours were done and recorded to determine the clay and silt content of the soil sample. A blank hydrometer reading was prepared by putting water in the 1 dm<sup>3</sup> sedimentation cylinder and mixed with sodium hexametaphosphate. Blank readings were recorded at 40 second and 2 hours. The readings obtained from the measurements were used to calculate percentages of sand, clay and silt in the soil sample. The USDA Textural triangle was used to determine the textural class of the soil using the calculated percentages of sand, silt and clay.

### **3.4.10 Bulk Density**

The bulk density of the soil was determined using the core ring method. A steel core ring was driven in the soil using a wooden block. A second core ring was placed over the first ring to drive it further into the soil until the first core ring was filled with soil. The core ring was then carefully removed after the surrounding soil was removed using a spade. Excess soil around the ring was removed using a steel knife. Soil protruding below the bottom and above the top of the sides of the core ring were cut off and removed. The mass of the soil with the ring was measured. The portion of the soil in the ring was removed and weighed and placed in weighing cans. The samples were oven dried at 105°C for 24 hours and allowed to cool. The weight of the oven

dried soil samples was determined. The moisture content of the soil was also determined from the difference between the soil in core ring before drying and the oven dry mass of soil. The volume of the core ring was also calculated from the height and internal diameter of the core ring. The oven dry bulk density of the soil was then calculated using equation 12

$$\text{Soil Bulk Density} \left( \frac{\text{g}}{\text{cm}^3} \right) = \frac{\text{Oven dry mass of soil volume in core ring (g)}}{\text{Volume of the soil in core ring (cm}^3\text{)}} \quad (12)$$

### 3.5 Sourcing and Characterization of Liming Materials

Four liming materials were purchased from local suppliers in Lusaka. Three of the materials were obtained in dry powder form while one was in aqueous suspension. The four liming materials were then analyzed for their acid neutralizing values (NV) and for their contents of Ca and Mg. In addition, the dry powder samples were subjected to particle size analysis which was then used to determine the Finess Factor (FF) of the materials.

#### 3.5.1 Determination of Neutralizing Values of Liming Materials

To determine the NV of liming materials, 1.0 g of the liming material was placed in a 250 mL conical flask to which 25 mL 1N HCl acid was added. A blank was also prepared by placing 25 mL 1N HCl acid into a 250 mL conical flask, heated and allowed to cool. A 100 mL distilled water was added and 5 drops of phenolphthalein indicator were added. This was allowed to cool. The mixture of liming material and HCL was heated on a hot plate until bubbling ceased, after which 100 mL of distilled water was added. The digest was allowed to cool after which 5 drops of phenolphthalein indicator were added. The blank and suspension were then titrated with 1N NaOH until the pink permanent colour appeared to mark the end point (Van Reeuwijk, 1993). The NV of the sample was calculated using equation 13:

$$\text{NV (\%)} = \left( \frac{N(\text{NaOH})(\text{eq/L}) * (\text{Vol of Blank} - \text{Volume of Sample}) (\text{L}) * \left( \frac{50 \text{g}}{\text{eq}} \right) *}{\text{weight of lime sample (g)}} \right) * 100 \quad (13)$$

### 3.5.2. Determination of Mg and Ca Contents of Lime Materials

To determine the Ca and Mg contents of the liming materials, 0.5g of air dry liming material was digested in 25 mL of 1N HCl in a 250 mL conical flask. The sample was placed on a hot plate and heated to point of boiling for 3 minutes. The digest was allowed to cool after which a 1 mL aliquot was obtained and placed in a 100 mL volumetric flask which was then filled to the mark with distilled water. A 10 mL aliquot was pipetted from this solution into a 25 mL volumetric flask to which a 5 mL solution of 5000 ppm  $\text{SrCl}_2$  solution was added. The solution in the flask was then filled up to the mark with distilled water. Standard solutions for Mg were prepared with concentrations ranging from 0.5 mg/L to 1.5 mg/L. Standards solutions for Ca were prepared with concentrations ranging from 0 to 5 mg/L. Concentrations of Ca and Mg in the sample extracts were determined by AAS using a Perkin Elmer Analyst 400 Spectrophotometer. Concentrations of Ca and Mg in the lime samples were calculated using equation 14:

$$\% \text{ Ca or Mg} = \left( \text{Conc} \left( \frac{\text{mg}}{\text{L}} \right) * \text{DF} * \frac{\text{g}}{1000 \text{ mg}} * \frac{\text{Vol of Extract(L)}}{\text{mass of lime sample(g)}} \right) * 100 \quad (14)$$

where: DF = Dilution factor, Conc = Concentration of cation.

### 3.5.3 Determination of the Fineness Factor

To determine the fineness of the liming materials, 100 g of lime sample was passed through a set of 2 mm and 250  $\mu\text{m}$  sieves. The lime particles retained on the 2 mm sieve, 250  $\mu\text{m}$  sieve and in the collection pan below the 250  $\mu\text{m}$  sieve were collected, weighed and expressed as a fractional percentage of the original mass of sample subjected to sieving. These measurements on each sample were done in triplicate. To determine the fineness factor for each lime sample, the FF was calculated using equation 15:

$$\text{FF} = \left( \frac{[(\% \text{ on 2mm sieve} \times 0) + (\% \text{ on 250}\mu\text{m sieve} \times 0.5) + (\% \text{ on Collection pan} \times 1)]}{100} \right) \quad (15)$$

Where: factors 0, 0.5 and 1.0 are proportions of lime expected to react in one season.

### 3.5.4 Calculation of Effective Neutralizing Value

The ENV of the liming materials was calculated by multiplying the NV by the FF of the liming materials as presented in equation 16:

$$ENV = NV * \frac{FF}{100} \quad (16)$$

### 3.6 Determination of Lime Requirements

Lime Requirements (LR) of the soils were determined using the values of the exchangeable acidity of each soil using equation 17. This formula is based on the method of Kamprath (1980) for determining the lime requirement based on exchangeable Al. According to Kamprath (1980), when the soil in 1N KCl is 4.0 or more then the exchangeable acidity is essentially the same as the exchangeable Al.

$$\frac{LR(gCaCO_3)}{kg \text{ soil}} = \frac{2*(Exch.Acidity(cmol))}{kg \text{ soil}} * \frac{0.5gCaCO_3}{cmol \text{ acidity}} \quad (17)$$

To determine the amount of lime required for a specific liming material, the ENV of that liming material was used. The formula used to determine the amount of a given liming material required to neutralize the exchangeable acidity of a soil is given by equation 18:

$$\frac{LR(gCaCO_3)}{kg \text{ soil}} = \frac{2*(Exch.Acidity(cmol))}{kg \text{ soil}} * \frac{0.5gCaCO_3}{cmol \text{ acidity}} * \frac{100}{ENV} \quad (18)$$

where: ENV = Effective Neutralizing Value of liming material. Exch acidity = Exchangeable acidity of soil.

The lime requirement per hectare was calculated using equation 19:

$$\frac{LR(kgCaCO_3)}{ha} = \frac{LR(gCaCO_3)}{kg \text{ soil}} * \frac{10^{-3}kg}{g} * \frac{kg \text{ soil}}{ha} * \frac{100}{ENV} \quad (19)$$

### 3.7 Determination of the Effect of Form of Agricultural Lime on Soil Acidity

From each liming material obtained in dry powder form, an aqueous suspension was prepared. This resulted in three dry powder forms and three aqueous suspensions forms from each source that supplied dry powder agricultural lime. With the additional one aqueous suspension, there were a total of seven liming materials tested and one control giving a total of eight treatments. The descriptions of the eight treatments used in the study are presented in Table 3. The aqueous formulations were prepared by adding the mass of dry powder lime required per kilogram of soil (Table 4) to 20 mL of distilled water for the laboratory study. The suspension was thoroughly shaken before being applied to the soil.

Table 3. Description of Treatments used in Both Laboratory and Field Studies

Treatment ID	Description of treatment	Formulation of Aglime
1	Soil + Aglime A	Aqueous suspension
2	Soil + Aglime B	Dry powder
3	Soil + Aglime B	Aqueous suspension
4	Soil + Aglime C	Dry Powder
5	Soil + Aglime C	Aqueous suspension
6	Soil + Aglime D	Dry Powder
7	Soil + Aglime D	Aqueous suspension
8	Soil alone (control)	None

Sources: A, B, C, and D used. Actual sources not disclosed for ethical reasons. Aglime=Agricultural lime.

The laboratory lime incubation experiment was laid out as a Completely Randomized Design with 8 treatments and four replicates per soil. One kilogram air dry soil was thoroughly mixed with calculated amount of agricultural lime required to neutralize the exchangeable acidity. Table 4 shows lime requirements of each soil and the actual application rates used for the different liming materials in the laboratory study.

The one kilogram sample of soils were then placed in 3 litre plastic pots and moistened to field capacity. The moist samples were then incubated for 120 days at room temperature in the glass house from the beginning of April to the end July 2016. The average daily temperature during this period was about 18.8 °C.

Twenty gram samples of soil were collected from each pot weekly during the first 5 weeks of the study and every fortnight thereafter to determine the pH of the soils in 0.01M CaCl<sub>2</sub> and the exchangeable acidity of the soils. The values of the pH and the exchangeable acidity were recorded after each measurement.

Table 4. Lime Application Rates Used on Two Soils in the Laboratory Study

Soil	Source of Liming Material	Standard Lime requirement (kg/ha)	Actual Lime Applied (g/kg soil)
Choma	A	5,400	1.65
	B	5,400	5.71
	C	5,400	1.60
	D	5,400	1.54
Chankukula	A	5,700	1.73
	B	5,700	5.97
	C	5,700	1.68
	D	5,700	1.61

### 3.8 Crop Trials

The crop trials were conducted at Liempe Farm located at 15° 23' 15'' South and 28° 28' 73'' East and the Agriculture Technology Demonstration Centre (ATDC) located at 15° 21' 25.02'' South and 28° 27' 27.20'' East. The experiments were carried out under-rain fed conditions in the 2015/2016 agricultural season.

### 3.9 Land Preparation

The selected fields at the two sites were ploughed using a tractor - mounted mouldboard plough. After ploughing, the land was disked to a fine tilth. The experimental plots were then pegged into blocks. Each block had 8 plots with dimensions of 4 m x 2 m separated by 1 m borders within blocks. The blocks were

also separated by 1 m border rows. Each site had 4 blocks, giving a total of 32 plots per site. The blocks were laid across a natural physiographic gradient or slope. The assumption was that the soil properties changed with the slope of the land. The blocking was intended to reduce changes in soil properties associated with change in the position of the land along the slope. The resulting experimental Design used at the two sites was a Randomized Complete Block Design (RCBD) with 8 treatments and 4 replications.

The treatments used at the two sites were described earlier in Table 4. The lime application rates used for the different liming materials at the two sites are presented in Table 5. The dry powder lime was broadcast uniformly across each plot and then incorporated into the soil using hand hoes. For the aqueous formulations made from the dry powder lime, the mass of dry powder lime broadcast across each plot (Table 5) was added to 5 litres of water in a watering can for the field trials and thoroughly mixed to form a suspension which was then uniformly applied across each plot as demonstrated in Figure 3. The agricultural lime was applied to the plots on 26<sup>th</sup> January, 2016.

Table 5. Lime Application Rates Used in Field Trials at Two Study Sites

Soil	Source of Liming Material	Standard Lime requirement (kg/ha)	Actual Lime Applied (kg/ha)
Choma	A	853	3000
	B	853	872
	C	853	862
	D	853	805
Chankukula	A	505	2,600
	B	505	510
	C	505	494
	D	505	472





Figure 3: Application of lime in aqueous form using a watering can at ATDC.

### 3.10 Management of Field Trials

On the 29<sup>th</sup> of January, 2016, Compound D fertilizer (10 % N: 20 %  $P_2O_5$ : 10 %  $K_2O$ : 6 % S) was applied to each plot along the rows at a rate equivalent to 200 kg/ha. This provided about 20 kg N/ha, 17.5 kg P/ha and 16.6 kg K/ha. Then an aluminium sensitive Soya bean variety *Spike* (Mutale *et al.*, 2014) was planted in each plot. The crop was planted in rows 45 cm apart, at a seeding rate of 20 seeds per meter, giving an approximate plant population of 444,444 plants per hectare.

There was a two week dry spell from 1<sup>st</sup> February to 13<sup>th</sup> February, 2016 which led to a poor emergence of seeds initially planted on the plots. Therefore, plots at both sites were replanted to fill in gaps left where earlier seeds failed to emerge. Weeding was



done three weeks after planting and again six weeks after planting. The weeding was done manually using hand hoes. Six weeks after planting in mid-March aphids attacked the crop. These were controlled by spraying the pesticide - Forate at a rate equivalent to 20 kg/ha.

The crop was harvested on 17<sup>th</sup> May, 2017. Plants from the four centre rows in each plot excluding two border rows on either side were harvested. The plants were cut above ground level and sun dried for one week. Subsequently, the pods were removed from each plant. Threshing was done manually by beating polyethene bags containing the pods with sticks to shatter the pods and release the grains from the pods. The grain obtained from each plot was weighed and recorded. The expected yield per hectare based on the mean values of grain obtained per plot was calculated using equation 20:

$$\text{Yield } \left( \frac{\text{kg}}{\text{ha}} \right) = \frac{\left( \frac{\text{kg grain}}{\text{rows harvested}} \right) * \left( \frac{\text{rows}}{\text{plot}} \right) * 10,000 \left( \frac{\text{m}^2}{\text{ha}} \right)}{\text{Area } \left( \frac{\text{m}^2}{\text{plot}} \right)} \quad (20)$$

The moisture content of the grain was then measured using a John Deere SW08120 Grain Moisture Tester. The final grain yield was reported as the adjusted yield at 12 % moisture content. The adjusted grain yield was calculated using actual grain yield using equation 21 below derived by Mr. Shitumbanuma (2016, Personal Communication):

$$\text{Yield } \left( \frac{\text{kg}}{\text{ha}} \right) = \frac{\text{Yield } \left( \frac{\text{kg}}{\text{ha}} \right) \text{ at actual moisture content}}{\left( 1 + \frac{\text{actual moisture content}}{100} \right)} * 1.12 \quad (21)$$

#### 4.0 Statistical Analysis

To determine whether there were significant differences among treatment means for the grain yield, an Analysis of Variance (ANOVA) was carried out. To separate the means, the Duncan's Multiple Range Test was used. Differences among the effects of the treatments were declared significant at  $P < 0.05$ . All statistical Analyses were conducted using SAS Statistical Software Package Version 9.1.3.

## CHAPTER FOUR : RESULTS AND DISCUSSION

### 4.1 Properties of the Soils used in the Studies

Selected chemical and physical properties of surface soils of Choma Soil Series from ATDC are presented in Table 6.

Table 6. Selected Chemical and Physical Properties of Choma Soil Series

Property	Units	Value	Critical Limit
pH(CaCl <sub>2</sub> 0.01M)		4.20	5.5
(Al <sup>3+</sup> + H <sup>+</sup> )	cmol.kgsoil <sup>-1</sup>	0.26	
Na <sup>+</sup>	cmol.kgsoil <sup>-1</sup>	0.02	
K <sup>+</sup>	cmol.kgsoil <sup>-1</sup>	0.20	0.22*
Ca <sup>2+</sup>	cmol.kgsoil <sup>-1</sup>	0.70	
Mg <sup>2+</sup>	cmol.kgsoil <sup>-1</sup>	0.16	
ECEC	cmol.kgsoil <sup>-1</sup>	1.34	
Al Saturation	%	19.4	15**
P	mg.kg <sup>-1</sup>	21.37	10.00
Cu	mg.kg <sup>-1</sup>	0.18	0.20*
Fe	mg.kg <sup>-1</sup>	22.54	2.60*
Mn	mg.kg <sup>-1</sup>	12.02	1.0*
Zn	mg.kg <sup>-1</sup>	0.61	0.50*
Organic matter	%	0.98	
Sand	%	84.30	
Silt	%	15.40	
Clay	%	0.30	
USDA Textural Class		Loamy sand	
Bulk Density	g.cm <sup>-3</sup>	1.66	

\* Sakala *et al.*, 2014.

\*\*Critical Al saturation for Soya bean (Juo and Franzluebbbers, 2003).

The soils at the ATDC were very strongly acid loamy sands with low organic matter, N, K and Mg. The Al saturation in this soil was 19.1 %, which was higher than critical Al saturation value of 15% soya bean cited by Juo and Franzluebbbers (2003). This

indicated that the levels of Al in the soils were likely to adversely affect soya bean growth and yield. The soils, however, had adequate levels of P and Ca for most crops. They also had adequate levels of Fe, Mn, and Zn, but low levels of Cu. Based on the textural class, the soils were likely to have a low water retention capacity and likely to be prone to water stress during periods of dry spells.

The major agronomic limitations of these soils were likely to be low chemical fertility due to their low organic matter content and low reserves of N, K, Mg, and Cu and strong acidity. Low water retention was also likely to make the soils prone to water stress. These soils thus required applications of agricultural lime to neutralize the soil acidity and organic amendments to increase the levels of organic matter and nutrient reserves and fertilizers to supplement the low levels of some nutrients.

A summary of chemical and physical properties of the Chakunkula soil from Liempe Farm is presented in Table 7. The surface soils at Liempe farm were sandy clay loams. They were also strongly acid, but had an Al saturation of 9.5 % which was lower than the critical value of 15 % for soya bean. Despite the low pH, soil acidity on this soil was not likely to adversely affect Soya bean growth and yield. In addition the soils contained low amounts of organic matter, total nitrogen, available P and K. They, however, had adequate levels of the micronutrients Fe, Mg, Cu and Zn. Based on their textural class, the water retention capacity of the Chakunkula soils was likely to be moderate to high. The major limitation of these soils for crop production was likely to be low chemical fertility, due to the low levels of organic matter, N, P and K. The productivity of the Chakunkula soil could be enhanced by adding suitable organic amendments, fertilizers and by liming them to neutralize the acidity.

Table 7. Selected Physical and Chemical Properties of Chakunkula Soil Series

Property	Units	Value	Critical Limit
pH (CaCl <sub>2</sub> 0.01M)		4.32	5.5
(Al <sup>3+</sup> + H <sup>+</sup> )	cmol.kgsoil <sup>-1</sup>	0.15	
K <sup>+</sup>	cmol.kgsoil <sup>-1</sup>	0.11	0.22
Na <sup>+</sup>	cmol.kg soil <sup>-1</sup>	0.02	
Ca <sup>2+</sup>	cmol.kg soil <sup>-1</sup>	0.92	
Mg <sup>2+</sup>	cmol.kg soil <sup>-1</sup>	0.37	
ECEC	cmol.kgsoil <sup>-1</sup>	1.57	
Al Saturation	%	9.55	15 %**
P	mgkg <sup>-1</sup>	6.55	10.00*
Total N	%	0.06	
Cu	mgkg <sup>-1</sup>	0.66	0.20*
Fe	mgkg <sup>-1</sup>	22.88	2.60*
Mn	mgkg <sup>-1</sup>	18	1.00*
Zn	mgkg <sup>-1</sup>	1.02	
Organic Matter	%	1.08	
Sand	%	58.50	
Silt	%	15.50	
Clay	%	26	
USDA Textural Class		Sand clay loam	
Bulk Density	g.cm <sup>-3</sup>	1.64	

\* Sakala *et al.*, 2014.

\*\*Critical Al saturation for Soya bean (Juo and Franzluebbbers, 2003).

## 4.2 Properties of Liming Materials

The properties of the liming materials used in the study are presented in Table 8.

Table 8. Selected Properties of Liming Materials

Source of Liming Material	CCE %	Finess Factor	ECCE	Ca	Mg
A	41.7	1.000	41.7		
B	88.9	0.998	88.7	38.4	1.1
C	91.6	0.998	91.5	38.9	0.8
D	95.6	0.995	95.1		

The critical properties of liming materials intended for agricultural use are their acid NV usually expressed by their CCE and their fineness, indicated by the FF. The two properties were used to calculate the ECCE by multiplying the CCE by the FF. In Zambia, materials sold as agricultural lime are expected to have an ECCE of at least 80% (Shitumbanuma, 2017, personal communication). Finely ground liming materials are generally preferable as they are more reactive than coarse grained materials.

Among the liming materials tested, lime source A, had the lowest ECCE while lime source D had the highest ECEC. All the liming materials were very fine with fineness factors of about 0.99, indicating that nearly all the lime would be expected to react with the soils within one season if water was not limiting.

## 4.3 Results from Incubation Experiments

### 4.3.1 Effect of the Form of Lime on Soil pH

The effect of the form of lime on the pH of Choma Soils over time is presented in Figure 4 below.

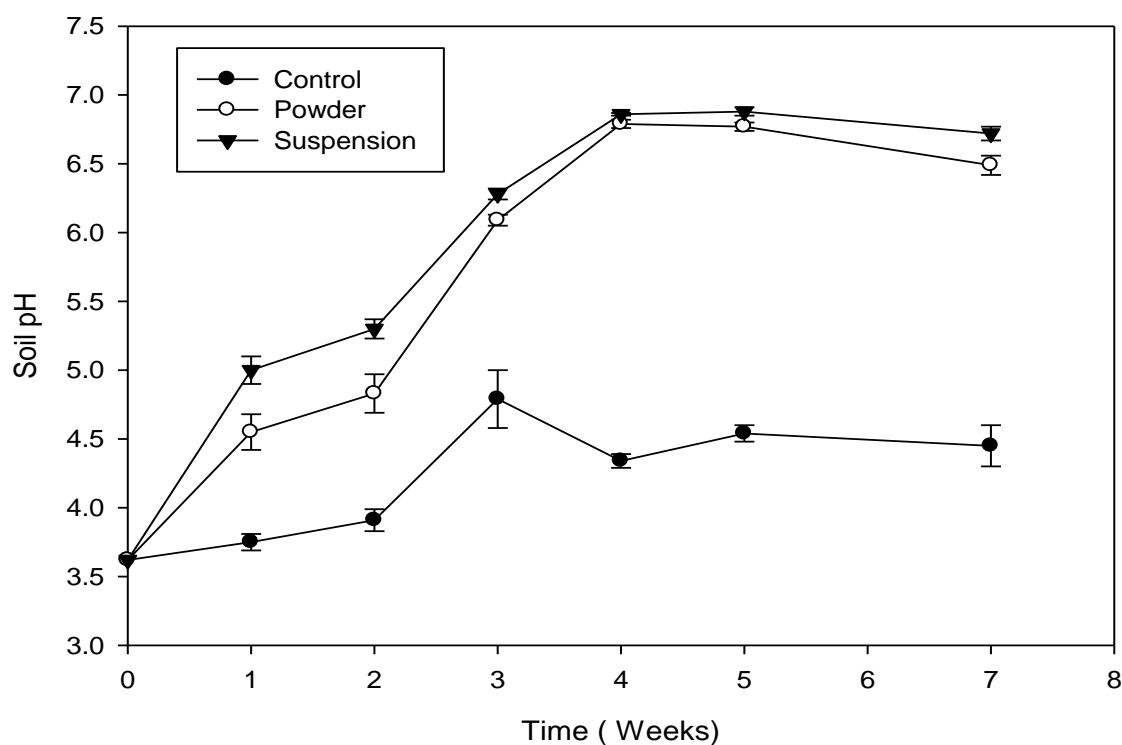


Figure 4: Effect of the form of lime on the pH of Choma Soil Series.

The results show that there was an initial sharp increase in pH of the limed soils in the first four weeks which stabilized up to about the 7<sup>th</sup> week. The pH of the unlimed soil also showed an initial increase in pH up to the 3<sup>rd</sup> week and stabilized thereafter, till the 7<sup>th</sup> week. Throughout the incubation period the pH values of the limed soils were significantly higher than those of the unlimed soil. For the limed samples, soils treated with aqueous formulations of lime had significantly higher pH values than those treated with lime in powder form from the first to the forth week and in the seventh week. No significant differences were observed between the pH values of the limed

samples in the 4<sup>th</sup> and 5<sup>th</sup> because both forms of lime reached their peak as most of the carbonate reacted with the acid. Thereafter, a gradual downward trend was observed.

The effect of the form of agricultural lime on the pH of Chakunkula soil series is shown in Figure 4. Limed soil samples had significantly higher pH than the unlimed soil sample throughout the incubation period. The limed samples had a sharp increase in soil pH from their initial pH in the first five weeks. From the 5<sup>th</sup> to 9<sup>th</sup> week, there was a minimal increase in pH. Soils treated with agriculture lime applied in aqueous suspension attained a consistently higher pH than soils with agricultural lime applied in dry powder form throughout the incubation period, although the differences in the pH were sometimes statistically non-significant.

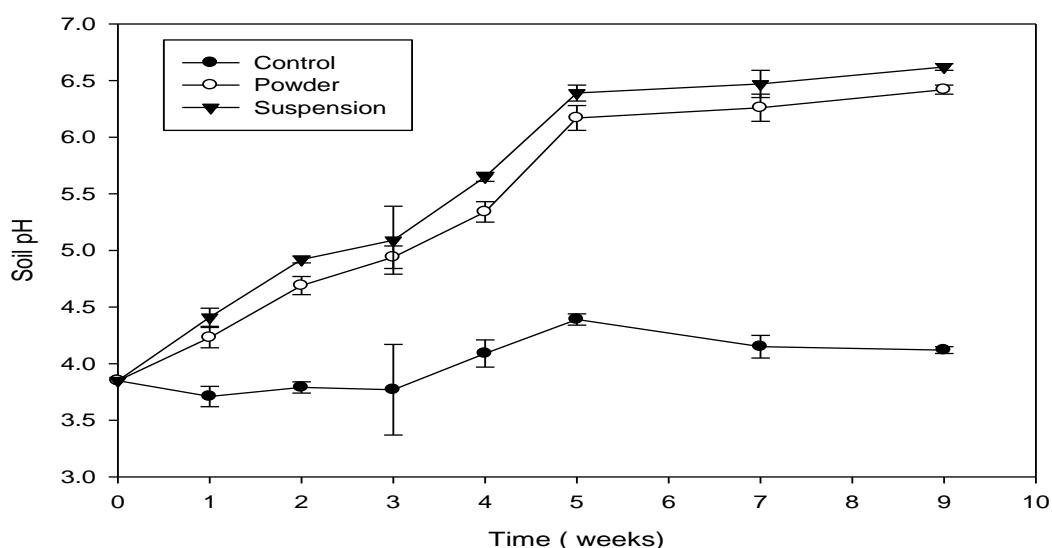


Figure 5: Effect of the form of lime on the pH of Chakunkula Soil Series.

In both soils, samples that received applications of agricultural lime had significantly higher pH than the unlimed samples throughout the study period. This was as expected since agricultural lime is known to neutralize acidity. The remarkable observation on both soils, was the consistently higher pH observed in soil samples to which agricultural lime was applied in aqueous form compared to the pH of soil to which

agricultural lime was applied in dry powder form. It is most probable that the higher pH observed in soils that received agricultural lime in aqueous form, was due to the earlier start of the chemical reactions involved in the acid neutralization processes compared to samples where agricultural lime was applied in dry powder form.

Agricultural lime, which is mainly composed of calcite ( $\text{CaCO}_3$ ), first needs to dissolve in water to release the  $\text{Ca}^{2+}$ , bicarbonate ( $\text{HCO}_3^-$ ) and hydroxyl ( $\text{OH}^-$ ) ion which are involved in various steps in neutralizing the acidity of soils and subsequently raising the pH of the soils. In soils where agriculture lime was applied in aqueous suspension, the dissolution of the lime started even before the lime was applied to the soil, while in soils where agricultural lime applied in dry powder form, the reactions started only after the soils were moistened. The soils were dry at the time lime was applied. Therefore, it is not surprising that soils that received lime in aqueous suspension had higher pH than soils that received lime in dry powder form. Further, Nielsen (1957) observed that the change in pH is faster at 25 % moisture content than at 10 %. Hence, the difference in the rates of reaction can also be attributed to moisture.

A small increase in soil pH was observed in the first five weeks in soil samples that were not limed. This increase was much less than that observed in samples that were limed. According to Wong *et al.*, (1998) the slight increase in the pH of unlimed soils could be attributed to organic molecules released from the decomposition of soil organic matter, which are reported to be able to consume protons from the soil solution and release  $\text{OH}^-$  ions into solution, leading to an increase in soil pH. The positive effect of soil organic matter on ameliorating soil acidity is well known and commonly mistaken as a liming effect. Lime, not only raises soil pH but also supplies Ca and Mg that are often deficient in acid soils.

#### **4.3.2 Rates of Increase in pH due to Liming on the Test Soils**

Differences were observed between the rates of increase in soil pH under different lime treatments on Choma and Chakunkula soils and consequently in the time it took



for the soils to attain a pH of 5.5. Table 9 presents results of the rates of increase in pH for the two soils with different lime treatments.

On both soils, treatments with lime applied in aqueous suspension had higher rates of increase in pH than treatments with powder agricultural lime. Choma soil had a mean increase of 0.64 pH units per week for treatments with lime in aqueous suspension but 0.60 pH units per week for samples for dry powder lime though these were not statistically different. On Chakunkula soil, samples with lime in aqueous form had a mean increase in pH of 0.52 pH units per week, compared to 0.48 pH units per week for treatments with dry powder agricultural lime though these were not statistically different.

Table 9. pH Increase and Time to Reach pH 5.5 for Choma and Chakunkula Soils

Soil	Treatment	$\Delta\text{pH}/\text{week}$	Time to attain pH 5.5 (weeks)	Average Time to Attain pH 5.5(weeks)
Choma	Aqueous Lime	0.64	2.5	$\approx 2.7$
Choma	Powder Lime	0.60	2.8	
Choma	No lime	0.16	NA	NA
Chakunkula	Aqueous Lime	0.52	3.8	$\approx 4.1$
Chakunkula	Powder Lime	0.48	4.4	
Chakunkula	No lime	0.12	NA	NA

Between the two soils, Choma Soil Series which had a loamy sand texture had a higher rate of increase in pH compared to Chakunkula Soil Series which had sandy clay loam texture. This indicates that Chakunkula soil had a higher pH buffering capacity than Choma soil. This observation was consistent with the fact that soils with higher clay content generally tend to have higher pH buffering capacities than coarse textured soils (Lungu, 2009).

The critical soil pH value for the managing acid mineral soils is reported to be 5.5 (Nduwumuremyi, 2013). This is the pH at which the levels of soluble Al in soils,

decline to levels that are not harmful for most crops. The results in Table 9 show that it took a slightly shorter time for soil treated with agricultural lime in aqueous suspensions to attain a pH of 5.5 than it took for soils treated with dry powder agricultural lime. On Choma soils, it took about 2.5 weeks or 18 days to attain a pH of 5.5 when aqueous suspensions of agricultural lime and 2.8 weeks or 20 days when dry powder lime was applied. On Chakunkula soil, it took about 3.8 weeks or 27 days to reach pH 5.5 with aqueous suspensions of agricultural lime and about 4.4 weeks or 31 days when lime was applied in dry powder form.

It took shorter time to attain a pH of 5.5 on both soils when agricultural lime was applied in aqueous suspension than when lime was applied in dry powder form. Furthermore, the mean rate of increase in pH was greater on Choma soil than on Chakunkula soil. It also took less time for the Choma soils to reach a pH of 5.5 than Chakunkula soil, suggesting that Choma soil Series had a lower pH buffering capacity than Chakunkula Soil Series.

These results generally indicate that agricultural lime applied in aqueous suspension was more effective in raising the pH of the soils than dry powder lime. These results are similar to those of Chansa (2016) who also observed that acid soils limed with agricultural lime in aqueous suspension had significantly ( $p < 0.05$ ) higher pH than those that to which agricultural lime was applied in dry powder form.

#### **4.3.3 Effect of the Form of Lime on Exchangeable Acidity**

Besides the effects of applying the two forms of agricultural lime on soils pH, it was also desired to know the effects of applying the different forms of agricultural lime on the exchangeable acidity of soils. It is usually the exchangeable Al in soils that is often responsible for the poor performance of crops on acid mineral soils. According to Kamprath (1970), for most mineral soils with pH of 4 or greater, most of the exchangeable acidity is due to the exchangeable Al. The changes in exchangeable acidity with time on Choma soils with and without lime are shown in Figure 5.

There was a rapid decline in the levels of exchangeable acidity with time for all three treatments. Throughout the incubation period, the lowest levels of exchangeable acidity were observed in soil samples that received agricultural lime in the forms of aqueous suspension. This was followed by samples to which agricultural lime was applied in dry powder whilst the highest levels of acidity were observed in soil samples that were not limed, as generally expected. Results of the levels of acidity are consistent with the results of the pH measurements earlier presented and discussed which showed that agricultural lime applied in aqueous suspension was more effective in neutralizing soil acidity than agricultural lime applied in dry powder form.

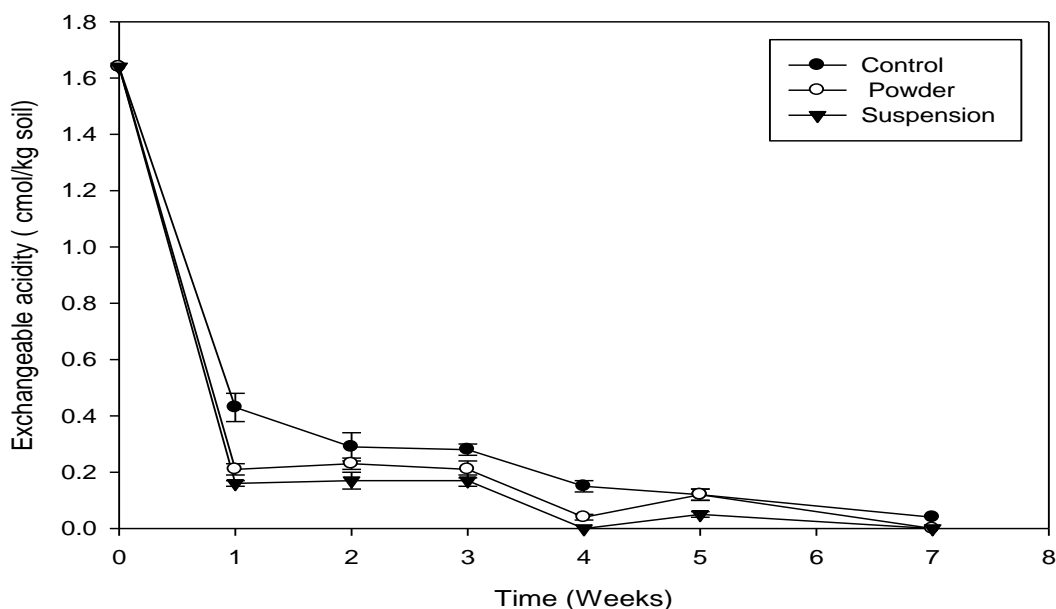


Figure 6: Effect of the form of lime on exchangeable acidity of Choma Soil Series.

The results show that applying agricultural lime significantly reduced levels of exchangeable acidity compared to unlimed soil. They also show that applying agricultural lime in aqueous suspension was more effective in reducing exchangeable acidity than to applying lime in dry powder form. The lowest levels of exchangeable acidity are observed in the 4<sup>th</sup> week, which corresponds to the week in which the pH of the soil reached its maximum value as shown in Figure 4. Increasing the pH of the soil

is associated with reducing levels of both the active and reserve acidity. Since the exchangeable acidity is a measure of the reserve acidity, the pH of the soil is expected to rise with decreasing reserves of acidity. The observed decline in the exchangeable acidity in the control could have been as a result of the increase in pH that was observed during the first 5 weeks of soil incubation as shown in Figure 3. The increase in pH according to Wong (1995) may be attributed to the production of organic acids, which contribute protons in solution. The increase in pH could partly have led to neutralizing some of the exchangeable Al. Furthermore, the organic acids produced during the organic matter decomposition could have complexed some Al resulting in a decrease in exchangeable acidity.

The effect of the form of lime on exchangeable acidity of Chakunkula Soil is shown in Figure 7.

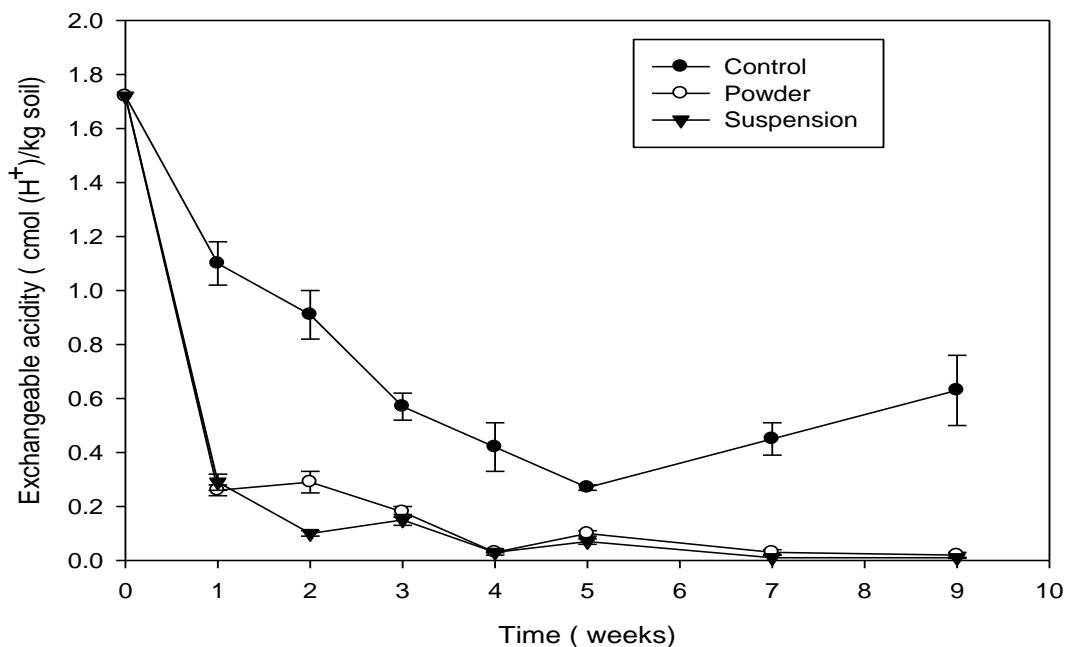


Figure 7: Effect of the form of lime on exchangeable acidity of Chakunkula Soil.

There was a sharp decline in the levels of exchangeable acidity in the first week of incubation study in the three treatments although the decline was significantly greater

in the limed samples than in the unlimed samples. The lowest levels of exchangeable acidity in the limed samples were observed in the 4<sup>th</sup> week, which corresponds to the time the limed sample attained a pH of 5.5.

Soils treated with lime had significantly lower levels of exchangeable acidity than the unlimed samples from the first week to the last week of the experiment. No significant differences in the levels of exchangeable acidity were observed between samples treated agricultural lime in aqueous suspension and agricultural lime in dry powder form except in the 2<sup>nd</sup> week, indicating that on Chakunkula soil, the two lime formulations were equally effective in reducing exchangeable acidity. The unlimed sample in Chakunkula soil series showed a reduction in the exchangeable acidity in the first five weeks and an increase thereafter. According to Wong *et al.*, (1985) the initial decrease in exchangeable acidity could be attributed to products of organic matter decomposition, in particularly low-molecular-weight-organic-acids form stable complexes with Al in soil solution and consequently reduced exchangeable acidity in the soil.

The increase in exchangeable acidity after the 5<sup>th</sup> week could be attributed to the further release of acid and CO<sub>2</sub> resulting from microbial respiration that could not be consumed by the organic compounds released by the organic acids earlier released into the solution. A natural phenomenon of soil re-acidification.

On Chakunkula soil, both forms of liming materials effectively reduced exchangeable acidity. This reduction in exchangeable acidity upon applying agricultural lime is consistent with results of several studies on the influence of lime on exchangeable acidity (Kapembwa, 2014; Nduwumuremyi, 2013; Peters *et al.*, 1996; Singh, 1985). According to Nduwumuremyi (2013) increased soil acidity causes solubilisation of Al, which is the primary source of toxicity to plants at pH values below 5.5. It is quite probable that most of the exchangeable acidity in Chakunkula soils is exchangeable Al, because the levels of acidity declined to values close to zero when the soil pH reached values close to 5.5.

The response of soil to the application of agricultural lime is greatly influenced by the buffering capacities of the soil. Chakunkula soil exhibited a higher buffering capacity and showed smaller difference in the levels of change exchangeable acidity when the two forms of lime were applied. On the other hand, Choma soil series with a lower buffering capacity showed a marked difference in the levels of exchangeable acidity between the two forms of agricultural lime. It seems that more pronounced differences in the levels of exchangeable acidity are likely to be observed between the two forms of lime when applied to soils with low buffering capacities than when they are applied to soils with high buffering capacities. Soils with a high buffering capacity tend to resist appreciable change in soil pH because they are highly buffered owing to a higher ECEC. According to Brady (1984), the higher the exchange capacity of a soil, the greater will be its buffering capacity other factors being equal. It was, therefore, not surprising that, the effect of the form of lime on the levels of exchangeable acidity on Chakunkula soil was not appreciably different between the two forms of lime. The results observed on Chakunkula soil are similar to those reported by Chansa (2016) who also found no significant ( $p < 0.05$ ) differences in the levels of exchangeable acidity on Misamfu Soil Series, an Ultisol with high buffering capacity when treated with lime in aqueous suspension and lime in dry powder form.

#### **4.4 Effect of Lime Application Form on Soya bean Grain Yield**

##### **4.4.1 Chakunkula Soil Series**

The soya bean grain yield adjusted to 12 % moisture content from different lime treatment plots on Chakunkula soil are presented in Figure 8. The mean grain yield varied from 1,250 to 1,460 kg/ha on Chakunkula soil series. The average grain yield for the site was 1,352 kg/ha which fell within the national average yield range for smallholder farmers reported to be from 1,000 kg/ha to 1,800 kg/ha (Prior, 1976) . However, the yield was below the national average yield of soya bean of 1,940 kg/ha for 2015/16 farming season (FAOSTAT, 2018). This average grain yield for the site was above the reported average yield for smallholder farmers of 900 kg/ha (Technoserve Report, 2011).

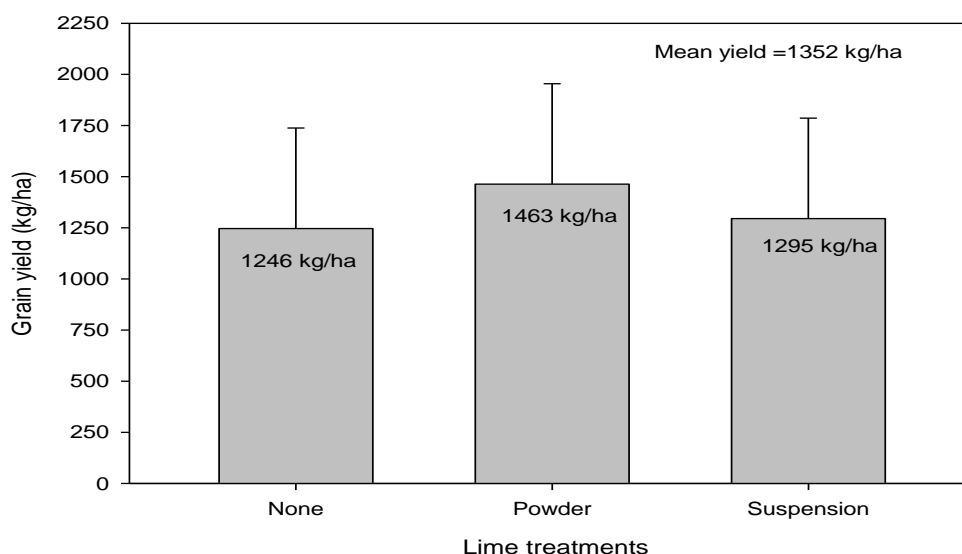


Figure 8: Average grain yield of soya bean on Chakunkula Soil.

No statistically significant ( $p < 0.05$ ) differences in grain yield were observed among the treatments used at the experimental site (Appendices 1 and 2). The lowest grain yield of 1,246 kg/ha was observed on unlimed plots while the highest grain yield of 1,460 kg/ha was obtained from plots that received applications of agricultural lime in dry powder form.

An analysis of the relative yields of soya bean from limed to the unlimed plots shows that the yield from plots that received agricultural lime in dry powder form was about 17 % greater than that of unlimed plots or equivalent to about 4 x 50 kg bags more than that of unlimed plots, while the yield of plots that received lime in aqueous suspension was only about 4 % greater than that of unlimed plots or equivalent to 1 x 50 kg bags more than the unlimed plots. The results show that there were very minimal differences between the soya bean grain yields of limed plots and those of unlimed plots on Chakunkula soil series.

The apparent lack of soya bean response to liming on Chakunkula soil can be attributed to a number of factors. A critical factor is the level of aluminium saturation. Soya bean is a relatively sensitive crop to aluminium and its yields decline significantly when the aluminium saturation in the soil exceeds 15 % (Juo and Franzluebbbers, 2003). Results of the initial soils tests on Chakunkula soils in Table 7 show that the Al saturation for this soil was 9.5 %, which was less than the critical level. This implies that the levels of Al in the soils were not likely to significantly reduce the grain yield of soya bean on this soil. Consequently, soya bean grown on this soil was not likely to show a significant response to liming. The observed relatively low yield responses to liming on Chakunkula soil of 4 % for lime applied with aqueous suspension and 17 % for lime applied in dry powder form are thus in agreement with expectations for a soil with such levels of Al saturation.

#### **4.4.2 Choma Soil Series**

The average grain yields of soya bean from different liming treatments on Choma soils series are presented in Figure 9. The mean grain yield on this soil was 1306 kg/ha, which was also within the average range for smallholder farmers. The yield on unlimed plots was 990 kg/ha while the highest was on plots treated with agricultural lime in aqueous suspension which had a mean yield of 1420 kg/ha. No statistically significant differences ( $P < 0.05$ ) were observed among the means yields of different treatments (Appendices 3 and 4). This result could be partly attributed to the great variability observed in the data, with a coefficient of variation of 44 %.

However, a relative comparison of the mean yields shows that the yield obtained from plots that received agricultural lime in aqueous suspension was about 43 % greater than that on unlimed plots or equivalent about 9 x 50 kg bags of Soya bean grain more than that of unlimed plots. This is a practically significant increase in yield for a smallholder farmer due to liming.



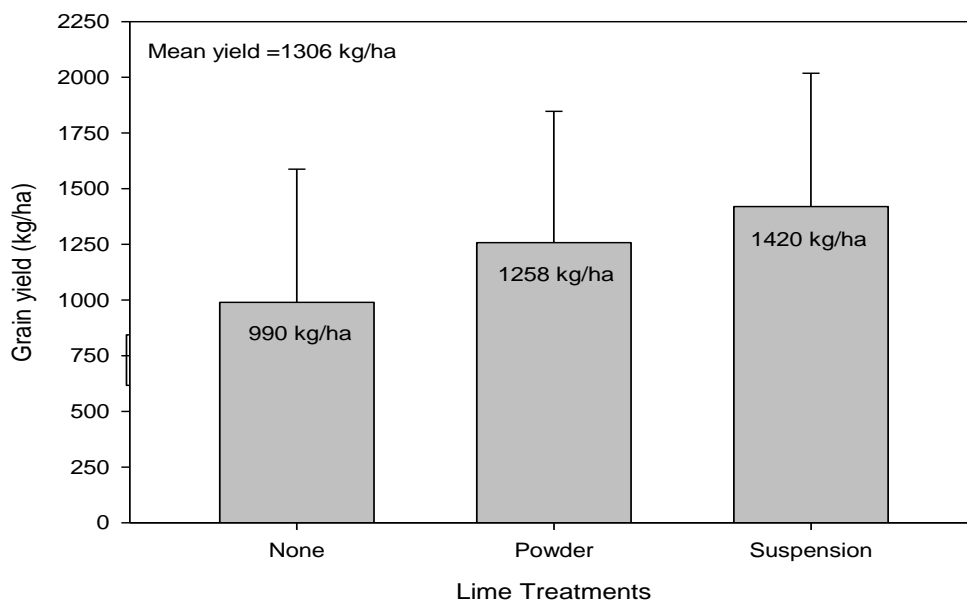


Figure 9: Average grain yield of soya bean on Choma Soil Series.

The yield from plots with agricultural lime applied in dry powder form was 27 % more than that of unlimed plots or an equivalent of 5 x 50 kg bags of soya bean grain/ha, which is a practically significant increase in yield. Therefore, despite the observed non-statistically significant differences in grain yield, the increases in grain yield due to liming on Choma soil of 5 x 50 kg bags of soya bean were practically significant because an increase of 250 kg soya bean grain is a significant increase in terms of the farmer's income even though statistically it may be considered non-significant.

Among the factors that could help explain the greater grain soya bean yield response to liming on Choma soils compared to Chakunkula soils is the initial aluminium saturation of the soils. Results in Table 6 show that the initial aluminium saturation on Choma soil was 19 % which was higher than the critical value for soya bean of 15 %. On the other hand, the Al saturation on Chakunkula soil was 9.5 % which was less than the critical values of 15 %. The aluminium saturation level on the Choma soil was high enough to significantly reduce grain yields from the optimum level if lime were not applied. On Choma soil series, liming was expected to result in significant increase

in the grain yield of soya bean. The observed 43 % and 27 % increases in yield due to liming in aqueous suspension and dry powder form respectively on Choma soils are thus in accordance with expectations.

Similar results have been observed in other crops. Abruna *et al.*, (1979), in their trial on liming sweet potato grown on tropical Oxisols and Ultisols found a positive relationship between the level of Al saturation and yield response to liming. They observed that the greatest response to liming occurred on soils with an aluminium saturation of more than 60 %. A study in Nigeria by Nwachuka (2008) on the effects of liming on maize yield grown in 12 strongly acidic soils under greenhouse conditions showed that maize grown on soils with aluminium saturation values ranging from 1-5, 15-28 and 26-33 % showed no responses, marginal and marked response to liming respectively. Hence, the magnitude of yield response to liming depends on the level of Al in the soil with high responses expected from soil with high levels of Al saturation and lower or no response from soil with low levels of aluminium saturation. Other workers such as Lungu and Chinene (1993) reviewed literature on cropping and soil management systems and their effect on soil productivity in Zambia and concluded that crop responses to liming varied with the soil and that not all acid soils respond to liming except those with high levels of Al saturation.

## **CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS**

### **5.1 Conclusion**

This study has shown that agricultural lime applied in aqueous suspension was more effective than dry powder agricultural lime in raising soil pH on both Choma and Chakunkula soils. The time required to raise the pH of the acid soils to 5.5 was shorter when the agricultural lime was applied in aqueous suspension than when it was applied in dry powder form on both soils. On Choma soil, agricultural lime applied in aqueous suspension was more effective in reducing exchangeable acidity than agricultural lime applied in dry powder form. No significant difference was observed between the effectiveness of lime in aqueous suspension and lime in dry powder form in reducing exchangeable acidity on Chakunkula soil.

No statistically significant differences in soya bean grain yield were observed between plots treated with agricultural lime in aqueous suspension form and plots treated with agricultural lime in dry powder form at both sites. Higher grain yield responses of soya bean to liming were observed on Choma Soil Series which had a higher initial Al saturation of 19 % than on Chakunkula soils which had a lower initial Al saturation of 9.5 %. Yield increases associated with liming were 43 % for lime in aqueous suspension and 27 % for lime in dry powder on a poorly buffered Choma soil. On Chakunkula soil, yield increases due to lime applied in aqueous suspension was only 4 % and that due to lime applied in dry powder form was 17 %. The results of this study have demonstrated the potential advantages of applying agricultural lime in aqueous suspension form compared to applying it in dry powder form.

### **5.2 Recommendations**

Based on the results of this study, it is recommended as follows:

- i. That where feasible, agricultural lime be applied to the soil in aqueous suspension for greater effectiveness especially in minimum tillage operations where crop residues are left in the field.

- ii. That lime in powder be applied to the soils at least 3 weeks prior to planting to allow the lime to react with the acid in the soils before the crop is planted.
- iii. That this study be undertaken hopefully in a season when rainfall would not be a limiting factor to growth and yield of soya bean on the effects of the two lime forms on Soya bean grain yield.

## REFERENCES

- Abruna, F., J. Vincente-Chandler., J. Rodriguez., J Badillo and S. Silva. 1979. Crop Response to Soil Acidity Factors in Ultisols and Oxisols in Puerto Rico. Journal of the Agricultural University of Puerto Rico. 63: 250-267.
- Anetor, M. O and E. A. Akinrinde. 2006. Response of Soya Bean [*Glycine max* (L.) Merrill] to Lime and Phosphorus Fertilizer Treatments on an Acidic Alfisols of Nigeria. Pakistan Journal of Nutrition. Vol.5 (3): 286-293.
- Banda, D. J. 2009. Soils of Zambia. In: Shitumbanuma, V. (Edit). Soil Acidity and Liming. Training Material for Extension Staff: The University of Zambia, Department of Soil Science, Lusaka. Pp 9-16.
- Barber, S. A. 1984. Liming Materials and Practices. In: Adams (Edit). Soil Acidity and Liming. 2<sup>nd</sup> Edition. Agronomy 12: Pp 173-210. American Society of Agronomy, Crop Science of America and Soil Science Society of America. Madison Wisconsin. U.S.A.
- Bast L., D. Warncke, D. Christenson. 2011. Facts About Soil Acidity and Lime. Extension Bulletin E-1566. Department of Crop and Soil Sciences, Michigan State University. USA
- Bolan, N. S., D. C. Adriano and D. Curtain. 2003. Soil Acidification and Liming Interactions with Nutrient and Heavy Metal Transformation and Bioavailability. Advances in Agronomy. 78:215-272.
- Brady, N.C. 1984. The Nature and Properties of Soils. Macmillan Publishing Company. Pp 190-214.
- Carey, P., K. Quirine and M. Hunter. 2006. Liming Materials. Cornell University - Cooperative Extension, U.S.A.

Chansa, C. 2016. Comparative effect of CAL Lime and Ndola Lime on Soil Acidity, Phosphorus Availability and Maize (*Zea Mays L.*) Yield. BSc Research Report. Department of Soil Science, School of Agricultural Sciences, University of Zambia, Lusaka, 30p.

FAOSTAT. 2018. Agriculture Data, Agricultural Production. ([Http://www.fao.org/faostat/en/#data/QC](http://www.fao.org/faostat/en/#data/QC). Accessed 26.01.2019)

Fageria, N. K. and V.C Baligar. 2003. Enhancing Nitrogen Use Efficiency in Crop Plants. Adv. Agron. 88. Pp. 97–185.

Goma, H. C. and B. R Singh. 1993. Liming in Relation to Crop Production in Ultisols and Oxisols of Northern Zambia. Ecology and Development Paper No.4. The Agricultural University, Norway.

Havlin, J. L., J D. Beaton. S. Tisdale and W. L. Nelson. 2005. Soil Fertility and Fertilizers: An Introduction to Nutrient Management. 7<sup>th</sup> Edition. Prentice Hall, New Jersey. USA.

Hayness, R. J and R. Naidu. 1998. Influence of Lime and Fertilizer and Manure Applications on Organic Matter Content and Soil Physical Conditions: A Review. Journal of Nutrient Cycling in Agroecosystems. Vol. 51:123-127.

Hede, R. A., B. Skovand and J. Lopez-Cesati. 2003. Acid Soils and Aluminium Toxicity. In: M. P. Reynolds., P. Ortiz and M. A McNab (Eds). 2001. Application of Physiology in Wheat Breeding. CIMMYT. Pp 172-182.

Helyar, K.R and W. M. Porter. 1989. Soil acidification, its measurement and the processes involved. In: Robson, A.D. (Ed.). Soil Acidity and Plant Growth. Australia, Academic Press. Pp 61-101.

Javaheri, F. 1976. Soya Bean Production Guide Based on How a Soya Bean Plant Develops. Research Branch. MAFF. Mt Makulu. Lusaka.

Jones, U. S. 1979. Fertilizer and Soil Fertility. Reston Publishing Company .Virginia, USA.

Juo, A. S. R and K. Franzluebbers. 2003. Tropical Soils; Properties and Management for Sustainable Agriculture. Oxford University Press. New York. USA.

Kamprath, E.1980. Soil Acidity in Well Drained Soils of the Tropics as Constraints to Food Production. Pp 171-187.In: Priorities for Alleviating Soil Related Constraints to Food Production in the Tropics. International Rice Research Institute and New York State College of Agriculture and Life Science. Cornell University. International Rice Research Institute. Philippines.

Kamprath, E. J. 1970. Exchangeable Al as Criterion for Liming Leached Mineral Soils. Soil Sci. Soc. Amer. J. Vol. 34 No. 2, Pp. 252-254.

Kapembwa, C. 2014. Evaluation of Chemical Reactivity of Local Liming Materials to Improve the Quality of Acidic Soils in Zambia. Msc Thesis. Ghent University. Brussels, Belgium.

Kumar, M., S. Hazarika, B. U. Choudhury., T. Ramesh., B. C. Verma and., I. J., Bordoloi. 2012. Liming and Integrated Nutrient Management for Enhancing Maize Productivity on Acidic Soils of Northeast India. Indian. J. Hill Farming. Vol. 25 (1):35-37.

Langer, H., M .Cea, M. G. Curaqueo and F. Borie. 2009. Influence of Aluminium on the Growth and Organic Acid Exudation in Alfalfa Cultivars Grown in Nutrient Solution. J. Plant Nutr.Vol 32: 618 - 628.

Lungu, I. O. 2009. Lime Requirement and Its Determination. In: Shitumbanuma, V. (Edit). Soil Acidity and Liming. Training Material for Extension Staff: The University of Zambia, Department of Soil Science. Lusaka. Pp 38-50.

Lungu, O. I and R. F. P. Dynoodt. 2008. Acidification from Long Term Use of Urea and its Effect on Selected Soil Properties. African. J. Food Agriculture Nutrition and Development: Vol. 8, No. 1. Pp. 63-76.

Lungu, O. I and V. R .N. Chinene. 1993. Cropping and Soil Management Systems and Their Effects on Soil Productivity in Zambia. Review Ecology and Development Paper No: 5. Agricultural University of Norway, Aas, Norway.

Magai, R. N. 1985. Field Tour Guide. Pp 342 – 468. In: Woode. P. R (Edit). Proceeding of the XI<sup>th</sup> International Forum on Soil Taxonomy and Agro technology Transfer Zambia. July 15<sup>th</sup> to August 1<sup>st</sup> 1985. IBSNAT, BADDC, MAWD, NORAD, USAID, SUSS and UNZA. Lusaka. Zambia.

Mambo, A and L. K. Phiri. 2003. “Soil Reaction (pH) in the Soils of Zambia: Memoir Accompanying the Soil Reaction (pH) Map of Zambia.” The Republic of Zambia, Mt. Makulu Central Research Station, Chilanga, Zambia.

Mayz, M. J and P. M. Cartwright. 1984. The Effect of pH and Aluminium Toxicity on the Growth and Symbiotic Development of Cowpeas. Journal of Plant and Soil Science. 80: 423 - 430.

McCauley, A., C, Jones and K, Olson-Rutz. 2017. Soil pH and Organic Matter. Nutrient Management. Module Number 8. Montana State University. Extension Department. USA.

McKenzie, R.C., L. W. Penney., B .Hodgins., S. Aulakb and H. Ukrainetz. 2008. The Effects of Liming on an Ultisols in Northern Zambia. Communications in Soil Science and Plant Analysis Journal. Vol. 19: 1355-1369.

Mclean, E. O. 1971. Potential Beneficial Effect from Liming: Chemical and Physical. Soil and Crop Society of Florida Proc. 31: 189-196. USA.

Mattiello, L., M. Kirst., F. R. Da Silva., A. R. Jorge and M. Menossi. 2010. Transcriptional Profile of Maize Roots under Acid Soil Growth. BMC Plant. Biology. [Http://www.biomedcentral.com/1471-2229/10/196](http://www.biomedcentral.com/1471-2229/10/196). (Accessed March, 2016).



Muchinda, M. R and O. C. Spaargaren. 1985. The Agro-climate of Zambia. In: Woode .P. R (Edit). Proceeding of the XI<sup>th</sup> International Forum on Soil Taxonomy and Agro technology Transfer Zambia. July 15<sup>th</sup> to August 1<sup>st</sup> 1985. IBSNAT, BADDC, MAWD, NORAD, USAID, SUSS and UNZA. Lusaka. Zambia.

Mulungwe, K., G, Tembo and S. Kabwe. 2013. An Economic Analysis of Precision Application of Lime at Reduced Rates. Journal of Economics and Sustainable Development. Vol. 4:17.

Mutale, P., D. Lungu and K, Miyanda. 2014. Response of Soya beans (Glycine Max) to High Levels of Aluminium in the Soil. *Zambian Journal of Agricultural Science*: Vol.10:1

Nduwumuremyi, A. 2013. Soil Acidification and Lime Quality: Sources of Soil Acidity, Effects on Plant Nutrients, Efficiency of Lime and Lime Requirement. Research and Review. *Journal of Agriculture and Allied Sciences*. Vol. 2. Issue 4.

Nielsen, K. F. 1957. Rate of Change of pH in Some Soils Due to Liming. *Can. J. Soil. Scie*. Vol: 41: 63 - 181.

Nyarko, F. O. 2012. Ameliorating Soil Acidity in Ghana: A Concise Review of Approaches. *Journal of Science and Technology*: Vol. 2, Special Issue, ICESR ISSN 2225-7217. (Online).

Nwachuka, J. K. 2008. The Effect of Lime Levels on the Growth of Beans and Maize and Nodulation of Beans in Three Tropical Acid Soils. *Communications in Soil Science and Plant Analysis Journal*. Volume 15. Pp: 1017-1027.

Okpara, D., C. O. Muoneke and N. Ihediwa. 2007. Influence of Liming on the Performance of High - Yielding Soya Bean Varieties in South-eastern Nigeria. *Agro-Science Journal*. Vol. 6 (2):16-24.

Peters, J. B., A. K. Kelling and E. E. Schulte. 1996. Choosing Between Liming Materials. Co-operative Extension Publication. University of Wisconsin. USA.

Phiri, L. K., M. Mwale and R. Banda. 2006. Nutrient Availability and Soil Test Summaries for Small Holder Farms in Some Districts in Eastern, Central and Southern Provinces of Zambia. Proceedings of the 1<sup>st</sup> Workshop on the Promotion of the Use of Agriculture Lime by Small Scale Farmers Held on 20<sup>th</sup> October 2006 at Suwilanji Gardens in Lusaka, Zambia. UNU/INRA-Mineral Resource Unit. Pp 21-29.

Prior, A. J. 1976. Soya Bean Variety Introductions: 1974 – 1975. Research Branch. MAFF. Mt Makulu. Productive Farming. No. 31: 33 - 34.

Rousk, J., E. Baath., P. Brookes, C. Lauber. , L. Lozupone., J. G. Caporaso., R. Knight and N. Fierer. 2010. Soil Bacterial and Fungal Communities Across a pH Gradient in an Arable Soil. The International Society for Microbial Ecology Journal. Vol 10: 1751–7362.

Sakala, G., V. Shitumbanuma and K. Belinda. 2014. Evaluation of Placement Methods of Spot Applied Lime Combined with Manure for Effective Soil Acidity Management and Increased Crop Yields. GART Year Book 2014. Lusaka.

Singh, B. R. 1985. The Effect of liming in Oxisols and Ultisols. In: Woode .P. R (Edit). Proceeding of the XI<sup>th</sup> International Forum on Soil Taxonomy and Agro technology Transfer Zambia. July 15<sup>th</sup> to August 1<sup>st</sup> 1985. IBSNAT, BADC, MAWD, NORAD, USAID, SUSS and UNZA. Lusaka. Zambia.

Shitumbanuma, V. 2006. Quality Aspects of Agriculture Lime. Proceedings of the 1<sup>st</sup> Workshop on the Promotion of the Use of Agriculture Lime by Small Scale Farmers Held on 20<sup>th</sup> October 2006 at Suwilanji Gardens in Lusaka, Zambia. Pp: 30-36.

Sumner, M. E., M. V. Fey and A. D Noble. 1991. Nutrient Status and Toxicity Problems in Acid Soils. In B. Ulrich and Sumner (Eds). Soil Acidity. Springer, New York.

Swallow, E., B. Thompson., E. McDonald., J. Roper., B. Beaton., S. Mellish and J. Coffin . 2011. Lime Trials - Evaluating Changes in Soil pH and Crop Yields of Soya beans, Potatoes Following Application of Three Types of Limes to Acidic Soil on PEI. Potato Consulting Services Inc. USA.

Tabuchi, A and H. Matsumoto. 2001. Changes in Cell–Wall Properties of Wheat (*Triticum aestivum*) Roots During Aluminium Induced Growth Inhibition. *Physiol. Plant.* 112: 353-358.

TechnoServe Report. 2011. Southern Africa Soy Roadmap - Zambia Value Chain Analysis. November 2010 - February 2011. Lusaka. Zambia. Pp 32. (<https://www.technoserve.org/files/downloads/technoserve-bmgf-zambia.pdf>. Accessed 20.12.2016).

Tisdale, S., W. Nelson and J. Beaton. 1985. Soil Fertility and Fertilizers. 4<sup>th</sup> Edition, McMillan Publishing Company. New York, United States of America.

Tucker, M. E. 1988. Sedimentary Petrology. Blackwell Scientific Publications. Oxford. United Kingdom.

Van Der Pol, F. 1992. Soil Mining. An Unseen Contribution to Farm Income in Southern Mali. Bulletin 325. Royal Tropical Institute. Amsterdam. Netherlands.

Van Reeuwijk, L. P. 1993. Procedures for Soil Analysis. 6<sup>th</sup> Edition. International Soil Reference and Information Centre (ISRIC) .FAO, Wagenigen, Netherlands

Von Uexküll, H. R and E. Mutert. 1995. Global Extent, Development and Economic Impact of Acid Soils. In: R. A Grunden. N. J Rayment., G. E Probert., G. E Probert (Eds). Plant-Soil Interaction at Low pH: Principles and Management. Proceeding of the 3<sup>rd</sup> International Symposium on Plant – Soil Interaction at Low pH. Brisbane Queensland, Australia. 12 - 16<sup>th</sup> September, 1993. Kluwer Academic Publishers. India.

Wong, M. T. F., S, Nortcliff and R. S. Swift. 1998. Method for Determining the Acid Ameliorating Capacity of Plant Residue Compost, Urban Waste Compost, Farmyard Manure and Peat Applied to Tropical Soils. *Commun Soil Sci Plant Anal.* 29: 2927-2937.

Yost, R. S. 2000. Plant Tolerance of Low Soil pH, Soil Aluminium and Soil Manganese. *Plant Nutrient Management in Hawaii's Soils. Approaches for Tropical and Subtropical Agriculture* J. A. Silva and R. Uchida (Eds). College of Tropical Agriculture and Human Resources, University of Hawaii at Manoa.

Yerokun, A. O. 2006. Smallholder Tool for Determining Lime Requirement in the Field. University of Zambia. Lusaka. Zambia. *Proceedings of the First Workshop on the Promotion of the use of Agriculture Lime by Small Scale Farmers. Held on 20<sup>th</sup> October, 2006 at Suwilanji Gardens in Lusaka, Zambia.* UNU/INRA Mineral Resource Unit Pp 8-20.

Zambia Agricultural Research Institute. 2002. Soya Bean Production Guide. Soils and Crop Research Branch. Lusaka. Zambia. Pp 1 – 9.

Zhenge, S. J. 2010. Crop Production on Acidic Soils. Overcoming Aluminium Toxicity and Phosphorus Deficiency. *Annals of Botany* .Vol.106: 183–184.

## APPENDICES

### Appendix 1: ANOVA Table for Soya Bean Yield on Chakunkula Soil Series

#### Class Level Information

Class      Levels    Values

Type                    3      None Powder Suspension

Number of observations    32

Dependent Variable: Yield

Source	DF	Squares	Sum of Mean Square	F Value	Pr > F
Model	2	245794.365	122897.182	0.56	0.5766
Error	29	6350086.604	218968.504		
Corrected Total	31	6595880.969			

R-Square    Coeff Var    Root MSE    Yield Mean

0.037265    34.61020    467.9407    1352.031

### Appendix 2: DMRT for Soya Bean Yield on Chakunkula Soil

Note: This test controls the Type I comparison wise error rate, not the experiment wise error rate.

Alpha                    0.05  
Error Degrees of Freedom      29  
Error Mean Square            218968.5  
Harmonic Mean of Cell Sizes 7.578947  
NOTE: Cell sizes are not equal.  
Number of Means            2      3  
Critical Range      491.6    516.6

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Type
A	1463.4	12	Powder
A	1294.9	16	Suspension
A	1246.3	4	Control

### Appendix 3: ANOVA Table for Soya Bean Yield on Choma Soil Series

Class Level Information					
Class	Levels	Values			
Type	3	None Powder Suspension			
Number of observations		32			
Dependent Variable: Soya Bean Yield					
Sum of					
Source	DF	Squares	Mean Square	F Value	Pr > F
Model	2	639051.28	319525.64	0.99	0.3852
Error	29	9397158.74	324039.96		
Corrected Total	31	10036210.02			
R-Square	Coeff Var	Root MSE	Yield Mean		
0.063675	43.59307	569.2451	1305.816		

### Appendix 4: DMRT for Soya Bean Yield on Choma Soil

NOTE: This test controls the Type I comparison wise error rate, not the experiment wise error rate.

Alpha	0.05
Error Degrees of Freedom	29
Error Mean Square	324040
Harmonic Mean of Cell Sizes	7.578947
NOTE: Cell sizes are not equal.	
Number of Means	2 3
Critical Range	598.1 628.5

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	Type
A	1420.8	16	Suspension
A	1258.0	12	Powder
A	989.5	4	Control