Assessing the liming effect of ground eggshells relative to aglime on two texture contrasting acidic soils

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I would like to dedicate this work to my parents Cecilia and Piet Sebonela

I truly appreciate you for all the effort and the support you gave me

You are my heroes

ABSTRACT

Soil acidity is one of the major land degradation problems that affects almost 50% of the world's arable land. It is usually associated with toxicities of elements such as aluminum and manganese, deficiencies of calcium and magnesium, and reduced microbial activity and diversity. Consequently, all these factors can result in reduced crop yield and economic losses for the farmers. The current effective method of mitigating soil acidity is the application of lime. However, the costs associated with the acquisition of lime make it challenging for small-scale farmers to lime their soils since large quantities of lime are required for substantial effects. Alternative cost-effective liming materials have been sought and these include industrial by-products such as fly ash and stainless steel slag. However, there are environmental and health concerns about using these liming materials since they contain potentially toxic elements. Eggshells were discovered to be composed of almost 97% $CaCO_3$ and 40% pure calcium, which is similar to traditional aglime. Moreover, eggshells contain very small amounts of potentially toxic elements and thus would not pose the risk of food chain contamination. However, due to limited research of eggshells on soil application, the question remains on the effectiveness of eggshells as a liming material.

The aim of this study was to evaluate the liming potential of ground eggshells relative to aglime in two texture contrasting acidic soils, and their subsequent effect on the growth of Swiss chard (*Beta vulgaris L*). The soils used in the study were, sandy clay loam, which had an initial pH of 4.52 and sandy loam with an initial pH of 5.23. The set objectives of the study were then achieved through an incubation and greenhouse study for 120 days. Both studies showed that the application of both eggshells and aglime significantly increased the soil pH in comparisonto the control for all application rates in both soils, moreover, there was no significant difference between the two applied lime sources. The results also showed a quick response within 7 days from the application of the two lime sources. The subsequent effects of the applied liming sources in the incubation period of the study were analyzed through the exchangeable acidity and plant-available phosphorus, whereas the subsequent effect of the liming materials in the greenhouse study were analyzed through plant-available phosphorus and plant dry weight of Swiss chard. The applied lime sources completely neutralized the acidity in the soil, and the exchangeable acidity under the application of the two lime sources was significantly lower than the controls at all application rates. The plant-available phosphorus was not significantly different between the applied lime sources at all application rates and the controls, however, the two lime sources increased the plant-available phosphorus above 25 ppm, which is the minimum health level of

plant-available phosphorus. There was no significant difference between the two applied lime sources compared to the controls at all application rates on the plant dry weight. However, it was observed that Swiss chard growing at the 0 t/ha (control) in the sandy clay loam showed poor and stunted growth throughout the study while Swiss chard growing at the 0 t/ha (control) in the sandy loam did not exhibit poor and stunted growth. According to the study's results, eggshells have a similar liming effect as aglime and their dissolution rate is similar, therefore, eggshells can be used together with aglime or as a substitute of aglime in increasing soil pH.

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CHAPTER 1: INTRODUCTION

1.1 Background

The human population is continuously increasing and the pressure on agricultural production to meet everyone's nutrient requirements is on the rise. The earth's arable land is not expanding and the agronomic inputs to produce good quality crops are limited and costly. It is, therefore, crucial to utilize the available agronomic resources sustainably, so that future generations might also meet their food security needs. Food security means having both physical and economic access to healthy nutritious food required for a productive and healthy life. This greatly depends on farmers and the accessibility of agronomic inputs to produce healthy crops. For farmers to remain economically viable, the agronomic production inputs must be cost-effective.

Soil acidity is one of the major constraints on agricultural production in South Africa. It is estimated that approximately 5 million hectares (ha) of South African soils are extremely acidic with an additional 11 million ha being moderately acidic (Venter *et al.*, 2001). The soil pH is an important factor that influences the solubility of nutrients, which consequentially influences the biological, chemical, and physical properties of the soil. The critical threshold for soil acidity is 5.5 of which below, effects such as aluminum (Al) and manganese (Mn) toxicities, certain nutrient deficiencies and reduced microbial activity and diversity become problematic. Consequently, all these factors can result in reduced crop yield and economic losses for the farmers.

The current effective method of mitigating soil acidity is the application of lime. However, small-scale farmers are unable to purchase lime and suffer soil acidity problems due to high purchasing costs, which are further compounded by transportation costs since large quantities of lime are required for substantial effects (Coventry *et al.*, 1989). Moreover, the profit margins of farmers are reduced due to high input costs. As a result, effective and less costly alternative sources of lime are needed.

Alternative liming materials in agriculture include industrial by-products such as fly ash, wood ash, stainless steel slag, and metallurgical slag (Das *et al.*, 2006). The mineralogy and chemical composition of these industrial by-products suggest that they can be used as liming materials (Adriano *et al.*, 1980; Bilski *et al.*, 1995; Yunusa *et al.*, 2006). However, there are major concerns about using these materials in agriculture since they contain potentially toxic elements, which may contaminate the food chain.

Household eggshells were reported to contain 94 to 97% calcium carbonate ($CaCO_3$) (Burley and Vadehra, 1989). These figures were reported to be effective from the application of aglime; therefore, eggshells may provide an opportunity to reclaim acidic soils at a lesser price since they form part of domestic waste. The advantage of using eggshells as a liming material ranges from agronomic to environmental. Eggshells contain a high calcium carbonate equivalent (CCE), which ranges from 75% and above (Holmes *et al.*, 2011). This suggests that eggshells may potentially neutralize more acidity soils to acceptable levels. Eggshells contain very small amounts of potentially toxic elements and thus would not pose the risk of food chain contamination. As well, the use of a recyclable resource provides an opportunity to practice sustainable agriculture. However, due to limited research of eggshells on soil application, the question remains on the effectiveness of these materials as a liming source.

1.2 Problem statement

Soil acidity is a major limiting factor affecting crop production and commercially available traditional liming materials are costly. Consequently, farmers (especially small scale) are unable to purchase the liming materials even though they may face soil acidity problems, which limits crop production. This results in dire financial losses to the farmers and potentially threatens the food security within the country. Moreover, disposing of eggshells in landfills consumes valuable landfill space and the potential benefits of using eggshells for liming and nutrient provision to crops is also lost.

1.3 Justification

South Africans consume a lot of eggs and dispose eggshells after consuming the eggs, thereby throwing away a potential source of calcium. According to the Egg Industry Production Report for September 2020, the daily production of eggs for household consumption in South Africa exceeded 30 million and is estimated to increase annually. These figures were only for registered producers and therefore the actual number could be higher. One eggshell weighs up to 5.5 g and therefore, the monthly production of eggs can potentially produce about 4 950tons of eggshell lime. Moreover, the poultry industry recorded 966.1 million chickens that were slaughtered in 2020 suggesting that 996.1 million eggs hatched and this can potentially produce 5 313tons of eggshell lime. Eggshell's chemical composition is predominantly $CaCO_3$, which is what traditional liming materials are made of, but eggshells will be cheaper since they would have formed part of the domestic waste.

1.4 Aim of the study

The study was aimed at evaluating the liming potential of ground eggshells relative to aglime in two soil textural classes contrasting acidic soils, and its subsequent effect on the growth of Swiss chard.

1.5 Objectives of the study

i. To compare the dissolution rate between ground eggshell and aglime in two soil types.
ii. To assess the rate at which both the treatments increase soil pH and plant-available phosphorus in the soil.
iii. To evaluate the growth of Swiss chard under the application of ground eggshell and aglime.

1.6 Hypotheses

DISSOLUTION RATE

Ho**:** The dissolution rates of eggshells and aglime are not statistically different.

H_a**:** The dissolution rates of eggshells and aglime are statistically different.

SOIL pH AND PLANT-AVAILABLE PHOSPHORUS

Ho**:** There is no statistical difference between the effect of eggshells and aglime onsoil pH and plant-available phosphorus.

H_a**:** There is a statistical difference between the effect of eggshells and aglime on soil pH and plant-available phosphorus.

PLANT PERFORMANCE

Ho**:** There is no statistical difference between the effect of eggshells and aglime onthe growth of Swiss chard.

H_a**:** There is a statistical difference between the effect of eggshells and aglime on the growth of Swiss chard.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Soil acidity is one of the major land degradation problems that affects almost 50% of the world's arable land (Kochian *et al.*, 2004). It is determined by the quantity of hydrogen ions activity in the soil solution, which is influenced by climatic, biological, and edaphic factors (Beukes, 1997). In South Africa, there is a huge gap between the potential and actual crop yield as a result of soil acidity. As the soil pH decreases, the availability of certain nutrients decreases and elements such as aluminum become more concentrated in the soil solution, which then results in potential toxicities. This affects the growth and development of plants, which ultimately costs farmers through financial losses.

Liming acidic soils is a common practice used to neutralize soil acidity. Traditionally, lime is used to increase the pH of acidified soil to the desired level (Mahler, 1994). Alternatives to traditional lime have been sought and these include fly ash, wood ash, stainless steel slag, and metallurgical slag. However, the presence of heavy metals in these materials limits their usefulness (Ndoro, 2008). Eggshells, on the other hand, are a promising alternative since they have a similar chemical composition as traditional lime (Burley and Vadehra, 1989) but research investigating their effectiveness is lacking.

An eggshell is a thin calcareous semipermeable membrane on the outer layer of an egg. It is produced in the ovaries of a chicken through the process called ovulation, and the formation of an eggshell is the last process in the development of an egg (Taylor, 1970). The primary function of an eggshell is to protect an egg from physical damage and to prevent the entry of dirt and microorganisms. To the hen, an egg is a potential chick, and the shell serves not only as a protective covering but also as a source of calcium for the embryo and as a membrane through which the embryo respires (Taylor, 1970). In a study of an eggshell, chemical analysis showed that an eggshell is composed of approximately 97% $CaCO_3$ (Burley and Vadehra, 1989), and most of the research on eggshell quality adopted this as a fact. Furthermore, the quality of an eggshell is influenced by the quality of the feed that is given to the laying hen.

2.2 Soil acidity

2.2.1 Nature and causes of soil acidity

Soil acidity is classified into two main categories, namely the anthropogenic derived acidic soils and the naturally occurring acidic soils (Sumner and Noble, 2003). Anthropogenically derived acidic soils are a result of human activities that introduce hydrogen ions in the soil or remove the basic cations from the soil. The application of ammonium-based fertilizers can acidify the soil when hydrogen ions (H^+) are released during nitrification (conversion of ammonium to nitrate), and the more fertilizer applied (over-application), the acidifying potential is also increased (Barak *et al*., 1997). The industrial burning of fossil fuels produces sulfur dioxide and nitrogen oxides, which are emitted into the atmosphere and react with water, oxygen, and other atmospheric chemicals to produce sulfuric and nitric acid. These acids are later introduced into the soil through acidic rain and acidify the soil.

Naturally occurring acidic soils are mainly caused by acidic parent materials, high rainfall, and the decomposition of organic matter. The weathering of acidic parent rocks such as rhyolite and granite produces soils that are acidic as compared to soils that develop from the weathering of limestone (Prasad and Power, 1997). High rainfall may leach the soil's basic cations (calcium, magnesium, sodium and potassium)that buffer against soil acidity and without these cations, hydrogen ions will be concentrated in the soil, which then results in acidic soils (Spark and Swift, 2008). The decomposition of organic matter produces organic acids, which can acidify the soil (Swift *et al*, 1979). Moreover, the respiration of roots can produce carbonic acids, which can also acidify the soil (Sumner and Noble, 2003; Bloom *et al*, 2005). In addition to the above-mentioned factors, natural hazards such as volcanic eruptions can emit sulfur and nitrogen oxides in the atmosphere, which may result in acidic rain (Fioletov *et al*., 1998).

The increase in hydrogen ions in the soil as a result of the above-mentioned natural and anthropogenic factors decreases soil pH and as a result, the solubility of aluminum compounds is increased (Pawlowski, 1997). With the increased hydrogen and aluminum ions in the soil, aluminum ions displace the exchangeable basic cations, reducing the acid-neutralizing capacity of the soil (Essington, 2004). Consequently, the concentration of basic cations in the soil solution is increased and become vulnerable to leaching. If they are leached, then the acid neutralizing capacity of the soil decreases and the soil becomes progressively acidic (Bloom *et al.*, 2005).

2.2.2 Effect of soil acidity on plant growth

The low pH of acidic soils is unfavourable for the growth of most plants and microorganisms. Acidic soils are generally associated with elemental toxicities of aluminum (Al) and manganese (Mn) (Prasad and Power, 1997). At optimum soil pH levels (>5), Al is found in solid forms with other elements and is therefore, not toxic to plants, however, as the soil pH decreases (<5.5), materials that contain Al begin to dissolve, and this results in a higher concentration of Al ions in the soil solution (Prasad and Power; 1997). The high levels of plant-available Al influence the physiological and the biochemical processes of the plant, resulting in toxicities characterized by the suppression of shoot and root growth, and uptake of some plant nutrients such as Ca, Mg, K and N (Le-Bot *et al.*, 1990). In contrast to Al toxicities, high levels of Mn in the soil delay plant growth by interfering with the normal cellular metabolic activities of plants (Prasad and Power, 1997), moreover, the toxicities of Mn are further followed by the development of necrotic spots, puckering and leaf chlorosis.

The growth of a plant is largely dependent on the available soil nutrients, which are subsequently influenced by the soil pH. The soil pH affects the availability of soil nutrients by changing their form in the soil, with the few exceptions of some major plant nutrients such as N, K and S, which are less directly affected by soil pH (Le-Bot *et al.*, 1990). At higher pH (alkaline) levels, nutrients such as phosphorus are less available since they react with Mg and Ca to form less soluble compounds, and at lower pH (acidic) levels, phosphate ions react with Fe and Al to form less soluble compounds (Le Bot *et al.*, 1990) and most micro-nutrients are less available at pH > 7.5.

Soils contain many microorganisms such as bacteria, fungi, nematodes, and protozoans, which play a significant role in the fertility and health status of the soil. They are involved in many soil processes that improve soil structure and increase nutrient levels in the soil. Some of these processes include the decomposition of organic matter, nitrogen fixation, and mycorrhizae associations (O'Sullivan *et al.*, 2015). In a soil microbial inoculation experiment conducted by Megali *et al.* (2015), the results revealed that effective microorganisms (lactic acid bacteria, yeasts, phototrophic bacteria, and actinomycetes) have a significant positive effect on the growth and yield of plants as they reported a 16% increase in the growth of cornafter inoculation with these microbes.

Most soil microorganisms prefer a near-neutral pH range of 6 to 7 (O'Sullivan *et al.*, 2015). Once the pH falls below 6, the concentration of hydrogen ions starts to increase in the soil and hydrogen ions have been reported to have a direct effect on the microorganisms, which then results in the disruption of their cell membrane. This alters the production of enzymes and reduces microbial reproduction (O'Sullivan *et a*l., 2015). This also results in reduced microbial activity, which in turn reduces the rate of organic matter decomposition. Moreover, soil acidity favors the growth and reproduction of soil fungi (Rousk *et al.*, 2008) and this can cause an imbalance between soil bacteria and fungi. With an increased population of fungi in the soil, the invasion of fungal root pathogen can be imminent. Therefore, acidic soils are not ideal for most soil microbial activities and not optimum for most plant growth. It is therefore, essential to regularly test for changes in soil pH.

2.3 Amelioration of acidic soils

2.3.1 Neutralization of soil acidity

The most common practice that is used to ameliorate acidic soils in agriculture is the application of materials that contain lime ($CaCO_3$) (Foth and Ellis, 1996). Lime is any material or rock that contains at least 50% $CaCO_3$ in the form of calcite by weight (Foth and Ellis, 1996). The most commonly used limestone in agriculture is calcitic and dolomitic limestone (Prasad and Power, 1997). Calcitic lime is derived from deposits of primarily calcium carbonate, whereas dolomitic lime is derived from deposits of calcium carbonate combined with magnesium carbonate and contains much higher levels of magnesium; however, calcitic limestone dissolves faster than dolomitic limestone since it is more finer than dolomitic lime. In addition to agricultural limestone, the chemical composition and mineralogy of some natural products such as eggshells and wood ash suggest that they can be used as liming materials since their major component is $CaCO_3$ (Holmes *et al.*, 2011).

The process of ameliorating soil acidity involves a series of acid neutralization reactions that increase in soil pH and exchangeable bases (Ca and Mg) with a decrease in the availability of Al and Mn (Kinraide and Parker, 1987; Essington, 2004; Troeh and Thompson, 2005). The neutralization of acidic soils by a liming material is described in Figure 1 below with the respective equations. The acidity in the soil occurs in two forms, namely the active and reserve acidity. The active acidity is the amount of hydrogen ions present in the soil water solution whereas reserve acidity refers to the acidity that is adsorbed on the soil surfaces and organic matter particles. Acidic soils have more hydrogen ions on their surfaces and with the addition of $CaCO_3$, the lime dissolves into the soil solution to form Ca^{+2} and CO^{-2}. The calcium will move to the surface of the soil particles and replace the adsorbed hydrogen ions. The replaced hydrogen ions will then react with the carbonate in soil solution to form carbon dioxide and water. This results in less acidic soils. As the soil pH and Ca increase in the soil, the retention of Ca on the soil exchange complex is favored and Al ions are expelled into the soil solution (equation 1.3). The expelled Al ions will then undergo hydrolysis transforming to less available forms at higher pH (Essington, 2004).

Acidic soil + Lime = Neutral Soil + Water, Carbon Dioxide, Aluminum Oxide

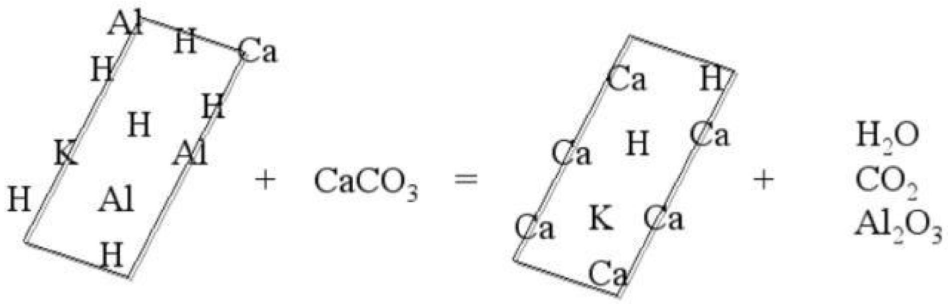

Figure 2.1: Schematic showing the neutralization of acidity in the soil.

$3CaCO_3\ (s) + 6H^+\ (aq) \longrightarrow 3Ca^{2+}\ (aq) + 3CO_2(g) + 3H_2O\ (l)$ (Eqn 1.1)

$3Ca^{2+}(aq) + 2AlX_3(ex) \longrightarrow 3CaX_2(ex) + 2Al\ +(aq)$ (Eqn 1.2)

$2Al(aq)^+ + 3H_2O(l) \longrightarrow 2Al(OH)_3\ (s) + 6H(aq)$ (Eqn 1.3)

Overall net equation

$3CaCO_3\ (s) + 2AlX_3\ (ex) + H_2O(l) \longrightarrow 3CaX_2(ex) + 2Al(OH)_3(s) + 3CO_2(g)$ (Eqn 1.4)

2.4 Effectiveness of alternative liming materials

The vast area of acidic soils and the high costs involved in reclaiming acidic soils has led to the investigation of alternative liming materials. Wastes such as industrial or domestic by-products are some alternatives since they may be cheap and promote sustainable agriculture. Alternative industrial by-products include wood ash, fly ash, stainless steel slag, and metallurgical slag while the household by-product includes eggshells (Tarkalson *et al.*, 2005; Adriano *et al.*, 1980). For these materials to effectively increase the soil pH, they should be composed of either oxides, hydroxides or carbonates of magnesium and calcium (Mahler, 1994). Moreover, the effectiveness of these materials is further influenced by the total neutralizing value (TNV), effective neutralizing value (ENV), fineness, and calcium carbonate equivalent (CCE) content (Mahler, 1994). The CCE value of the material compares the material to pure $CaCO_3$, which is an active ingredient in lime. Therefore, materials with higher CCEvalues can neutralize more acidity than materials with a lower CCE value per unit weight of the material.

The chemical composition of wood ash suggests that it can be an effective liming material since it has more than 30% $CaCO_3$ and a pH of 12.5 (Naylor and Schmidt, 1986). Naylor and Schmidt (1986) compared the changes in soil pH under the application of wood ash and limestone with the application rates of 0, 2.24, 4.5, 9.0, 19.9 and 35.9 metric tons/ha in acidic soil. The results for wood ash showed an increase in soil pH with an increase in the application rate, however, the limestone treatment increased the soil pH more significantly than wood ash. This was attributed to the equivalent neutralizing value of wood ash, which was 2 times less than that of lime. This suggests that more materials of wood ash are required for the same substantial effect as lime. These results were consistent with the report of Saunder (2014) in which the reported CCE value of wood ash was 25 to 29% while the CCE value of lime was 90 to 95%. Saunder (2014) concluded that it would require 2 to 4 times the amount of wood ash to achieve similar results as lime.

Fly ash has been reported to be effective in reclaiming acidic soils with a fineness efficiency rating of 99.6% as compared to that of lime, which is 90.6% (Ndoro,2008). This suggests that fly ash can react more quickly than lime since it has a large surface area and can therefore, potentially reduce the time taken to influence change in soil pH. However, there are reported cases of phytotoxicities due to its high concentrations of potentially toxic elements such as B, Mo and Se (Adriano *et al.*, 1980). The challenge of using fly ash is that applying too much can result in toxicities, which can contaminate the soil or cause plant injuries as reported by Ndoro (2008) while applying less might result in less substantial effects in reclaiming acidic soils. Therefore, thorough research and studies are still needed on application rates of fly ash.

Ndoro (2008) conducted a study analyzing the liming potential of stainless-steel slag and metallurgical slag (Calmasil) with 5 application rates, namely 0, 50, 100, 200, and 400% of the optimum recommended liming rate (OLR). In the study, it was found that stainless steel slag and metallurgical slag have a high liming potential since their CCE is 97%, which is similar to the reported CCE of lime. The results also showed that stainless steel slag and metallurgical slag had the highest crop yield at lower application rates as compared to lime, however, the application rates of >200% optimum recommended liming rate (OLR) caused injuries to the plants. It was reported that the injury to plants may be due to the toxic compounds such as nickel (Ni), cadmium (Cd) and chromium (Cr) that are found in stainless steel slag and metallurgical slag as reported by Pillay *et al.* (2003) and Shen *et al. (*2004). However, according to literature (Wang *et al*., 2010; Shen *et al*, 2004), there are reported cases of plant injury as a result of over-liming and therefore, over-liming could have caused plant injury since the possibility of it was not investigated in the study.

2.5. Liming and plant-available soil phosphorus

Phosphorus (P) is one of the seventeen essential elements that are required for plant growth and is the second most important macro-nutrient after N. It is naturally occurring and plays an important role in the biochemical processes of plants such as root growth, seed production, photosynthesis, respiration and other important plant processes (Foth, 1984; Gichangi *et al.*, 2008). The deficiency of phosphorus limits crop production in more than 40% of the world's arable lands (Vance, 2001) and additionally, the resources to add phosphorus are limited globally (Vance *et al.*, 2003). The deficiencies of plant-available phosphorus affect the developmental processes of the plant, which subsequently, results in delayed maturity, reduced plant growth, and a reduction in crop yield and quality (Gichangi *et al*., 2008).

Although phosphorus plays a significant role in the growth and metabolism of plants, it is the least plant-available macro-nutrient and is the most frequently deficient nutrient in most arable soils because of its low availability and poor recovery from fertilizers. In acidic soil conditions, phosphorus forms insoluble compounds with cations such as Al and Fe and in alkaline conditions, with Ca and Mg (Kochian *et al*., 2004). Moreover, P that is applied in the form of fertilizer is mainly adsorbed by the soil and due to this, large quantities of soil phosphorus are not directly plant-available (Smith, 2001; Vance *et al*., 2003). It was reported that approximately 80 to 90% of the applied P fertilizers cannot be absorbed by plants as a result of adsorption to iron oxides/hydroxides, Al hydroxides, Ca and Mg carbonates and chemical precipitation. In contrast to other nutrients such as nitrogen which uses mass flow and diffusion towards the plant roots, phosphorus is immobile in the soil. Therefore, approximately 1 to 5% of phosphate ions are transported via mass flow whereas large quantities of phosphate ions reach the plant roots through diffusion (Lambers *et al*., 2006). However, the diffusion coefficient of phosphorus is very low as compared to other nutrients (Clarkson, 1981). As a result, plants do not utilize the total volume of phosphorus in the soil, but only the quantity near the roots (Föhse and Jungk, 1983).

The application of lime in acidic soils is the current effective method of increasing soil pH and subsequently, the availability of added and native phosphorus. The increase in plant-available inorganic phosphorus as a result of liming has been ascribed to abiotic processes caused by pH increase, such as desorption of mineral bound phosphorus and reduced phosphorus sorption potential (Haynes, 1982; Sánchez and Salinas, 1981). However, according to Margenot (2018), there are possibilities of lime influencing plant-available phosphorus through biological phosphorus cycling. There are enzymes called phosphatases that are involved in the process of cycling phosphorus, and they are pH-sensitive (Nannipieri *et al*., 2011; Turner, 2010) and therefore, in acidic and alkaline soil conditions, their activities are reduced and eventually, the process of P cycling, which subsequently limits the availability of plant-available phosphorus.

2.6 Eggshells as a liming material

2.6.1 Alternative disposal for eggshells and their liming potential

Most food wastes contain some form of valuable minerals, and it is essential to find alternative uses of the valuable minerals from these food wastes to reduce the environmental concerns and high disposal costs. According to the Food and Agriculture Organization of the United Nations, it was estimated that the direct economic cost of food waste on a global scale was $750 billion in 2013 and was estimated to increase annually. Eggshells, like other food wastes, contain essential elements that make them beneficial in crop production.

According to Burley and Vadehra (1989), almost 94 to 97% of eggshells are $CaCO_3$ in the form of calcite, which is an active ingredient in liming materials. In addition to $CaCO_3$, eggshells contain some essential elements required for plant growth (Table 2-1). Moreover, it has been discovered that a good quality eggshellmay contain as much as 5.5 g of $CaCO_3$ (Zaman *et al.*, 2018).

Table 2.1: Chemical properties of an eggshell (Zaman *et al.*, 2018).

Chemical property	Amount (%)	Chemical property	Amount (%)
Calcium carbonate	97	Iron	0.1
Magnesium	0.2	Copper	0.1
Phosphorus	0.3	Manganese	0.1
Sodium	0.1		
Potassium	0.1	Organic matter	2

In relation to the traditional agricultural limestone, both eggshells and limestone are composed of more than 90% $CaCO_3$ and contain approximately 40% pure calcium (Burley and Vadehra, 1989). This level has been reported to be effective in neutralizing soil acidity from limestone applications. Therefore, eggshells should be effective in reclaiming acidic soils.

Since eggshells are chemically similar to limestone with $CaCO_3$ andcalcium levels, their function in the soil would be expected to be similar. Firstly, they increase the soil pH in acidic soils by neutralizing hydrogen ions and secondly, they provide calcium as a plant nutrient. Calcium is one of the essential nutrients for plant growth, which is responsible for plant cell wall integrity and for activating certain enzymes that coordinate cellular activities (Anil and Sankara, 2001). The deficiency of calcium in the soil is often characterized by necrosis in margins of young leaves, deformation of leaves, highly branched short root system, stunted growth and general chlorosis. This results in poor plant growth and development (Anil and Sankara, 2001).

In addition to the above-mentioned functions of calcium, it also plays a significant role in reclaiming sodic soils and maintaining soil's physical properties (Dontsova, 1998). Most clay soils have negative electrical charges, which repel each other thus creating dispersion, however, with an addition of a positively charged ion like Ca^{2+}, the clay particles will be flocculated (Dontsova, 1998). Soil flocculation results in soils that are naturally aggregated, which subsequently results in improved water infiltration and drainage (references). Moreover, the pore spaces for air and water storage are improved and thus provides a good habitat for soil biology and results in soils that are resistant to erosion. This indicates that eggshells can also be used as a soil stabilizer (Dontsova, 1998).

2.6.2 The effectiveness of ground eggshells as a liming material

Peer-reviewed literature on the effect of eggshells on soil pH and plant performance is lacking, and therefore, there is limited information on the liming effect ofeggshells. Most of the information on eggshells as a liming material is found on garden websites, which have major drawbacks of speculative information and flawed experimental design (Mitchel, 2005). Factors such as particle size, organic matter and dissolution rate of eggshells have not been thoroughly reported.

The dissolution rate is dependent on the nature of the eggshell (i.e., intact, crushed, or ground into a fine powder) and soil pH. Mitchel (2005) evaluated the usefulness of eggshells as a liming material in an acidic soil of pH 4.9. The study compared finely ground and hand-crushed/coarsely ground eggshells. The results of the study revealed that finely ground eggshells are an effective liming material since they increased the calcium content and pH of the soil. In contrast, the hand-crushed eggshells were reported to be ineffective as there were no changes in soil pH and calcium content. These findings suggested that grinding eggshells into fine powder improved their decomposition rate possibly by increasing the surface area of the eggshells. However, since the soil properties of the experiment were not given, the soil properties could have also contributed to the results since they also influence the decomposition process. Holmes *et al.* (2011) also reported a significant effect of ground eggshells as a liming material in research comparing ground eggshells and aglime. This indicates that there is a link between the effectiveness of eggshells and their fineness.

The decomposition rate of eggshells is largely influenced by the pH of the soil. Eggshells are essentially $CaCO_3$, which dissolves in acids and not in alkaline materials (Mitchel, 2005). Therefore, eggshells are more likely to decompose/dissolve more quickly in soils with a lower pH than in high pH. Mitchel (2005) reported that eggshells may stop having an influence on soil pH once the soil pH exceeds 6.8.

Holmes *et al*. (2011) compared the soil pH response under the application of agricultural lime and ground eggshells in acidic soil of pH 5.4. In the 6^{th} month, the results showed similar changes in soil pH for both the ground eggshells and aglime treatments. However, from the 18^{th} month, the eggshell treatment increased the soil pH more rapidly than the aglime. They cautioned that the reported effective calcium carbonate equivalent (ECCE) value of ground eggshells might be incorrectly low and suggested that the ECCE value of ground eggshells be increased 2 to 3 times more from the reported value based on the soil pH responses in their study. This was consistent with the study by Akinmutimi and Agwu (2014), which revealed a significant increase in soil pH under the application of ground eggshell; however, the increase in pH for this study was within 2 weeks.

The quantity of ground eggshell powder needed to increase the soil pH varies from soil to soil, depending on factors such as the soil parent material, forms of soil calcium and the climatic conditions of the area.

CHAPTER 3: MATERIALS AND METHODS

The study was aimed at evaluating the liming potential of ground eggshells in comparison to agricultural lime (aglime) in two soils of different textures. The study required the initial acquisition of liming materials and soils with subsequent characterization (section 3.1). The objectives of the study were then pursued through an incubation study (section 3.2) and a subsequent greenhouse study (section 3.3).

3.1 : Overall study preparation

3.1.1 Eggshell collection and characterization

Eggshells were collected from nearby food outlets (i.e restaurants, hotels, etc) and students residing at the North-West University campus. The eggshells were then cleaned with water, air-dried, ground with a coffee grinder, sieved through a 2 mm mesh and stored in polythylene bags under ambient conditions. Aglime (dolomitic limestone with 85% $CaCO_3$ and $MgCO_3$) was purchased from NWK in Mahikeng and was also ground and sieved through a 2 mm mesh. Both the ground eggshells and aglime were analyzed for mineralogy by X-ray diffraction (XRD) using an X-ray diffractometer. Agricultural lime was composed of $CaCO_3$, $MgCO_3$ and quartz (SiO_2) whereas ground eggshell was composed of $CaCO_3$ (Figure 3.1). The CCE of both aglime and eggshells were determined using the HCl method (Page *et al.*, 1982) and their values were 82.2% and 94.8%, respectively.

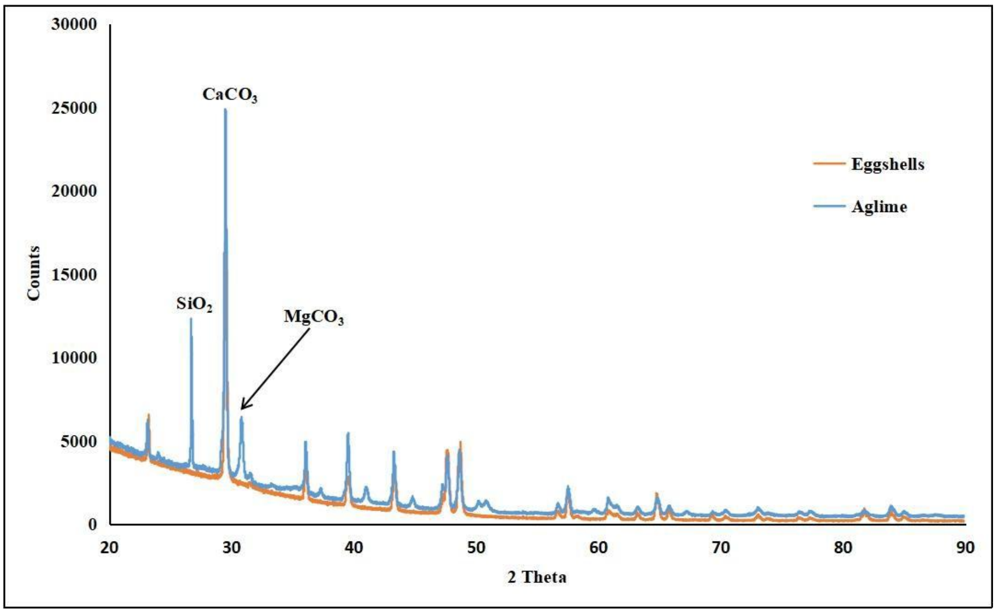

Figure 3.1: X-ray powder diffraction pattern of ground eggshell (orange) and agricultural lime (blue). The dominant peaks ($I/I_i = 100$) of the identified minerals are indicated.

3.1.2 Soil collection and characterization

Two acidic soils with different textures were collected from a depth of 0-20 cm from two recently ploughed farms on the outskirts of Ottosdal, North West province in South Africa (Figure 3.2). The sandy clay loam (soil C) was collected at coordinates (26°18'36.0''S 26°06'36.0''E) while the sandy loam soil (soil S) was collected at coordinates (26°24'00.0''S 26°06'36.0''E). The parent material for the sandy clay loam and sandy loam soils was Ventersdorp lava and granite respectively with both soils classified as Hutton (Soil Classification Working Group, 1991). The collected soils were air-dried, sieved with a 2 mm mesh and then stored in plastic bags in the greenhouse. Samples of the two soils were sent to the South African Sugarcane Research Institute Fertilizer Analytical Services (FAS) laboratory for analysis (clay content, organic matter, volume weight (density), exchangeable acidity, extractable Ca, Mg, K, Na, Fe, Mn, Zn, and Cu and resin extractable P) (Table 3.1). Further analysis of pH (KCl) and Mehlich 3 extractable P were determined in the university laboratory.

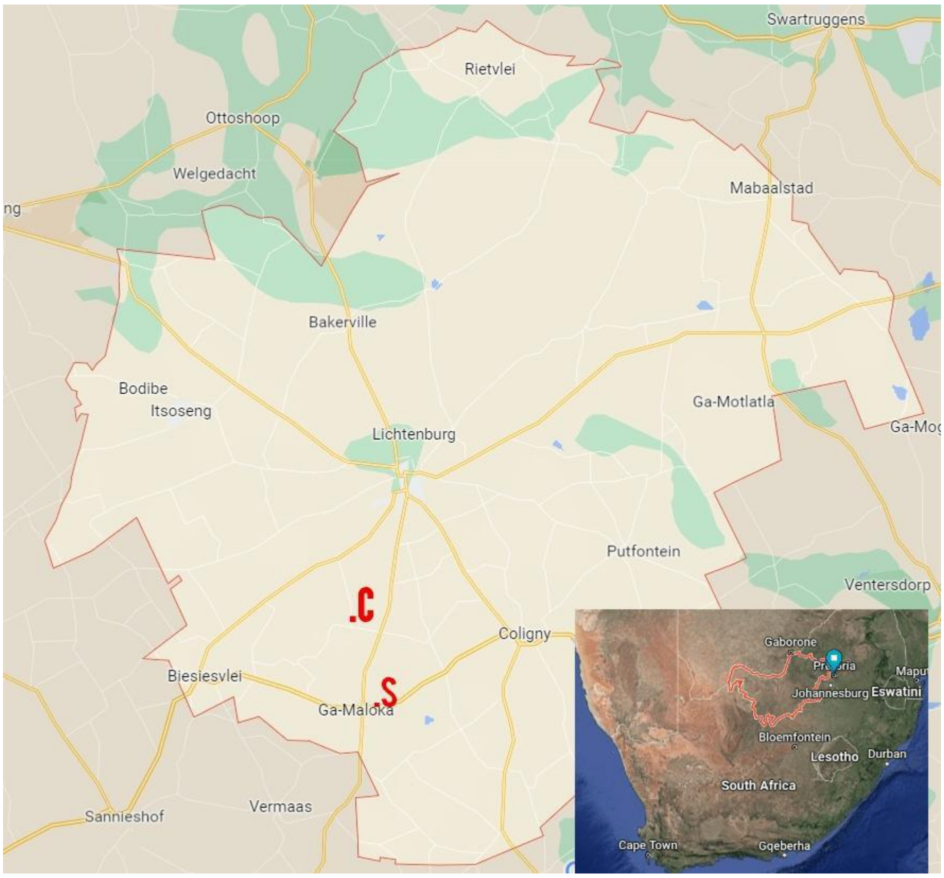

Figure 3.2: Location of the Hutton soils used in this study. The red letter C ((26°18'36.0''S 26°06'36.0''E) indicates the collection location of the sandy clay soil while the red letter S (26°24'00.0''S 26°06'36.0''E) indicates the collection location of the sandy loam soil.

Table 3.1: Physical and chemical properties of the two soils.

Analysis	Soil C	Soil S
Texture	Sandy clay loam	Sandy loam
pH (KCl)	4.52	5.23
Exchangeable acidity (Al+H) cmol/L	0.55	0.26
Total cations cmol/L	2.49	1.52
Volume weight g/mL	1.38	1.58
Acid saturation %	22.1	17.1
Phosphorus (P) mg/L	46.8	10.5
Potassium (K) mg/L	252	45
Calcium (Ca) mg/L	184	147
Magnesium (Mg) mg/L	44	47
Sodium (Na) mg/L	6	5
Zinc (Zn) mg/L	4.2	1.6
Copper (Cu) mg/L	2.3	0.7
Manganese (Mn) mg/L	138.5	16.6
Iron (Fe) mg/L	36	23
Clay MIR %	21	18
Organic matter MIR %	0.9	0.9

3.1.3 Determination of soil field capacity

The field capacity of both the soils was determined gravimetrically (Page *et al.*, 1982). Soil samples were placed in a glass beaker, and water was slowly poured into the glass beaker. The glass beakers were closely monitored until the downward movement of water had ceased. The wet soil was weighed into another beaker before it was oven dried for 24 hours. After 24 hours, the dried soil was weighed, and field capacity was calculated using the difference between the mass of wet soil and dried soil. The final calculated field capacity was 12.26% and 16.39% for sandy loam and sandy clay loam soils, respectively.

3.2 Incubation study

3.2.1 Aim of the incubation study

The aim of the study was to assess the rate at which both lime sources increase soil pH and plant-available phosphorus. The effect of eggshells and aglime on soil properties and their dissolution rates were assessed using an incubation experiment.

The incubation experiment was conducted in a laboratory for 120 days at room temperature (25°C).

3.2.2 Soil preparation for an incubation study

The two soils were weighed to 4 kg into 2 litre containers and were treated with aglime and eggshells at four application rates of 0 t/ ha, 1.0 t/ ha, 2.5 t/ ha and 5.0 t/ ha. The optimum application rate for the experiment is known to be 5.0 t/h (Anderson *et al*, 2013; Gazey and Andrew, 2010). The exact grams of eggshells and aglime to be added to 4 kg of soil were calculated using the measured soil volume weight/bulk density for each study soil. The soils were manually shaken for 15 minutes to promote the even distribution of the liming materials within each soil. The soil in each container was equally divided into six small polystyrene foam cups to allow for destructive sampling during the length of the study (Figure 3.3).

Figure 3.3: Layout of the incubation experiment containers showing each treatment with six small foam cups for destructive sampling.

3.2.3 Incubation study design and layout

The experiment was a factorial design using two soils with different textures and two liming materials (eggshells and aglime), which were applied at four rates and replicated three times. The soils were watered to field capacity (Section 3.1.3) and were completely randomized in the laboratory and left open to promote aerobic conditions and decrease reaction time. The soils were watered two times a week with distilled water to field capacity until sampling.

3.2.4 Data Collection

Samples were collected on days 7, 14, 30, 60, 90 and 120 for analysis (soil pH (ASTM, 1995), exchangeable acidity by titration (Mclean, 1965) and plant-available P using a spectrophotometer after Mehlich 3 extraction (Borissova and Mitropolitska, 1979).

3.2.5 Statistical analyses

The collected data was subjected to analysis of variance (ANOVA). Variables that showed a significant effect on measured data were subjected to HSD (Tukeys procedure).

3.3 Greenhouse study

3.3.1 Aim of the greenhouse study

The aim of the study was to evaluate the growth of Swiss chard under the application of ground eggshell and aglime. A greenhouse experiment was conducted at the North-West University experimental farm (Molelwane).

3.3.2 Soil and seedling preparation for the greenhouse study

Soil preparation

Eight kilograms of each collected soil (sandy clay loam and sandy loam) was put into pots and then treated with eggshell and aglime at the four experimental application rates of 0 t/ ha, 1.0 t/ ha, 2.5 t/ ha and 5.0 t/ ha. The amount of eggshells and aglime to add to each pot containing 8 kg of soil was calculated using the measured soil volume weight/bulk density for each study soil.

Seedling preparation

A 10-litre bucket was filled with hygromix and was watered to the saturation point. The hygromix was thoroughly mixed and used to fill a polystyrene seedling tray of 200 holes. After planting Swiss chard seeds in all the holes, the seedling tray was placed on top of the table. The seedlings were irrigated three times a week, with one irrigation being supplemented with 2 grams of urea.

After six weeks, the seedlings were transplanted using one seedling per pot as mentioned above. The transplanted seedlings were further supplemented with 2 grams of NPK fertilizer two times during their growing period with a one-month split period. The pots were irrigated two to three times a week depending on the weather and until the termination of the experiment.

3.3.3 Greenhouse study design and layout

The experimental design for the experiment was a 2x2x4x3 factorial, with 2 soils (sandy clay loam and sandy loam), 2 liming treatments (eggshells and aglime), 4 treatment rates (0, 1.0, 2.5 and 5.0 t/ha) and three replications. The pots were randomly placed in the greenhouse as shown in Figure 3.4. All the pots were irrigated two times a week for four weeks before transplanting.

Legend

C = Sandy clay loam soil; S = Sandy loam soil
A = aglime; E = eggshells
0, 1, 2.5 and 5 = Application rate
R1-3 = Replication number

Figure 3.4: The complete randomization of the pot experiment.

3.3.4 Data collection

Both plant and soil data were collected for the greenhouse experiment. The data collected for the greenhouse experiment were plant yield, soil pH (KCl) and available phosphorus of the soil. The yield data was collected at the end of the experiment. The leaves of the Swiss chard were washed with water and oven-dried for 24hrs at 80^{o}C and were subsequently weighed and recorded. The plant-available phosphorus was extracted with the Mehlich 3 solution and then analyzed using a spectrophotometer at the wavelength of 650 nm (Borissova and Mitropolitska, 1979). The soil pH was analyzed using a 1 M KCl with soil to solution ratio of 1:2,5 (ASTM, 1995).

3.3.5 Statistical analyses

The collected plant and soil data was subjected to analysis of variance (ANOVA). Variables that showed a significant effect on measured plant and soil data were subjected to HSD (Tukeys procedure).

CHAPTER 4: RESULTS

4.1 INCUBATION EXPERIMENT

4.1.1 Soil pH

Adding aglime and eggshells significantly increased the soil pH in both the sandy loam and sandy clay loam soils (Figures 4.1 and 4.2). The soil pH increased rapidly initially and then plateaued after day 7 for both lime sources added to the sandy clay loam and 14 days for the sandy loam. The rate of increase was greatest for the highest application rate (5 t/ha) in sandy clay loam soils. Although the applied treatments significantly increased the soil pH, there was no significant difference between aglime and eggshells in increasing the soil pH at all application rates in both soils.

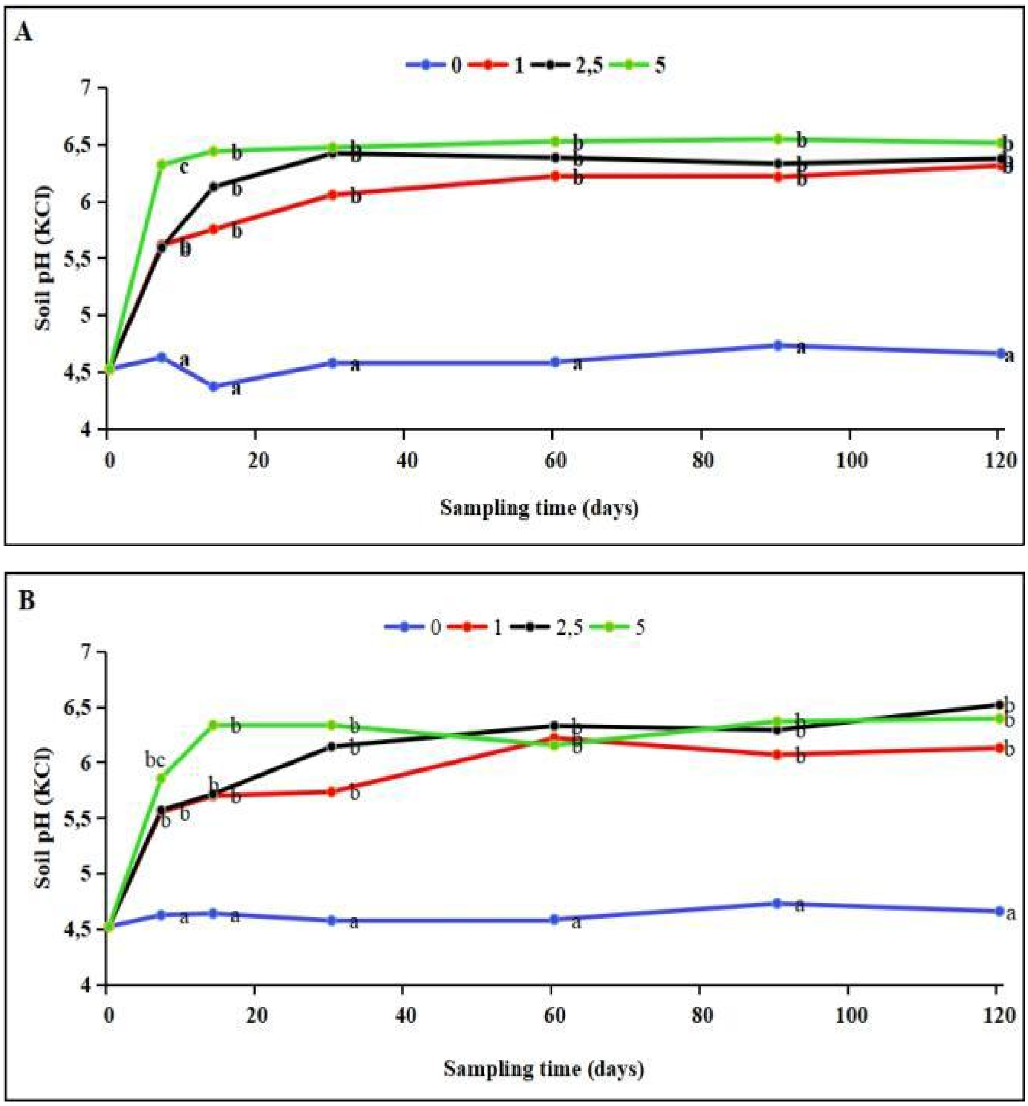

Figure 4.1: The effect of applied eggshells (A) and aglime (B) at four application rates (0, 1, 2.5, and 5 t/ha) on the soil pH (KCl) of sandy clay loam over 120 days of the incubation study.

Different letters indicate a significant difference (0.05) in soil pH between liming treatments(source and rates) for each sampling day using the Tukeys HSD test.

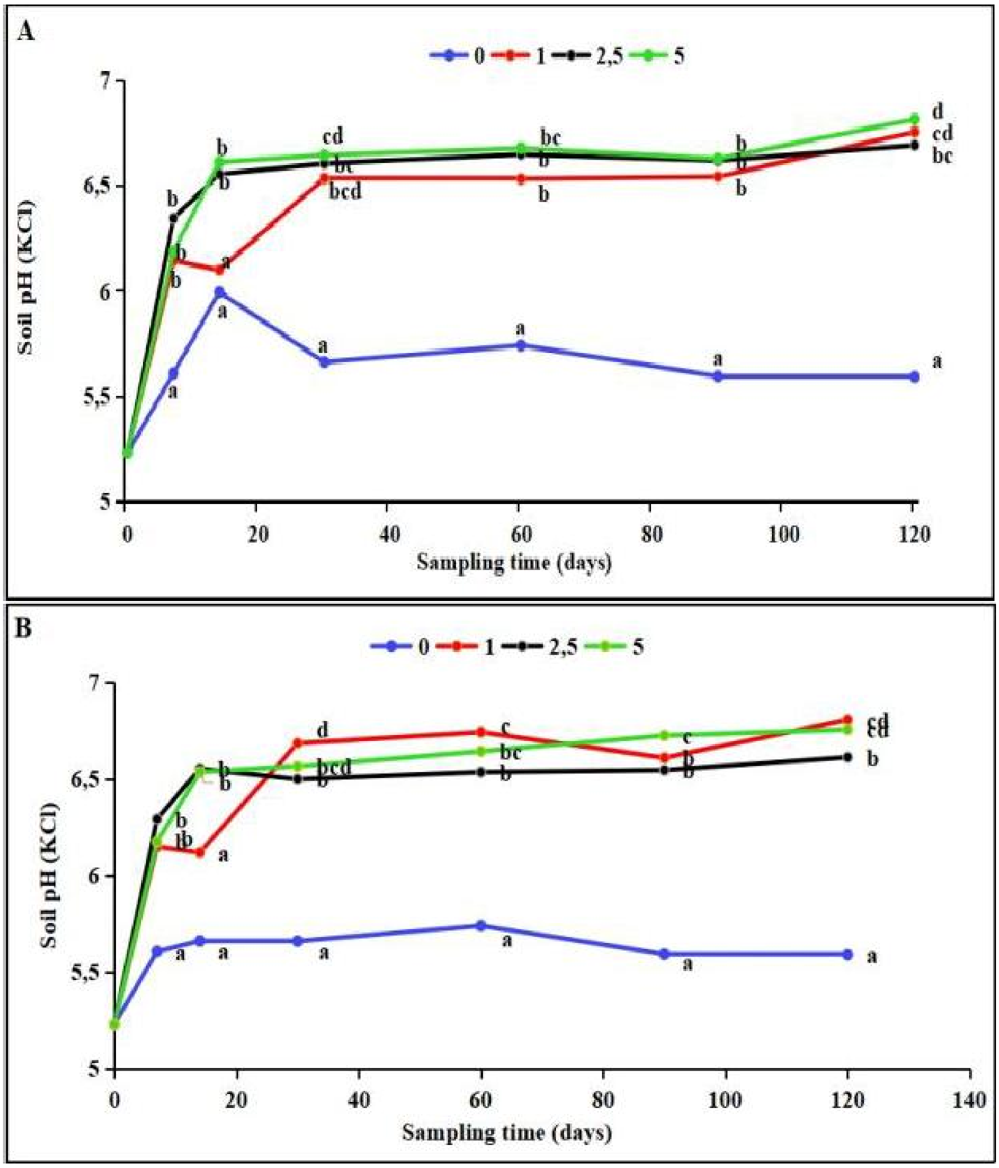

Figure 4.2: The effect of applied eggshells (A) and aglime (B) at four application rates (0, 1, 2.5, and 5 t/ha) on the soil pH (KCl) of sandy loam over 120 days of the incubation study. Different letters indicate a significant difference (0.05) in soil pH between liming treatments (source and rates) for each sampling day using the Tukeys HSD test.

Moreover, there was no significant difference between the application rates of 1, 2.5 and 5 t/ha for each source. After 120 days, the soil pH under the application of eggshells and aglime in both the soils, was significantly higher than the controls at all application rates. Furthermore, there was no significant difference between the two lime sources at all application rates (Figure 4.3 and 4.4).

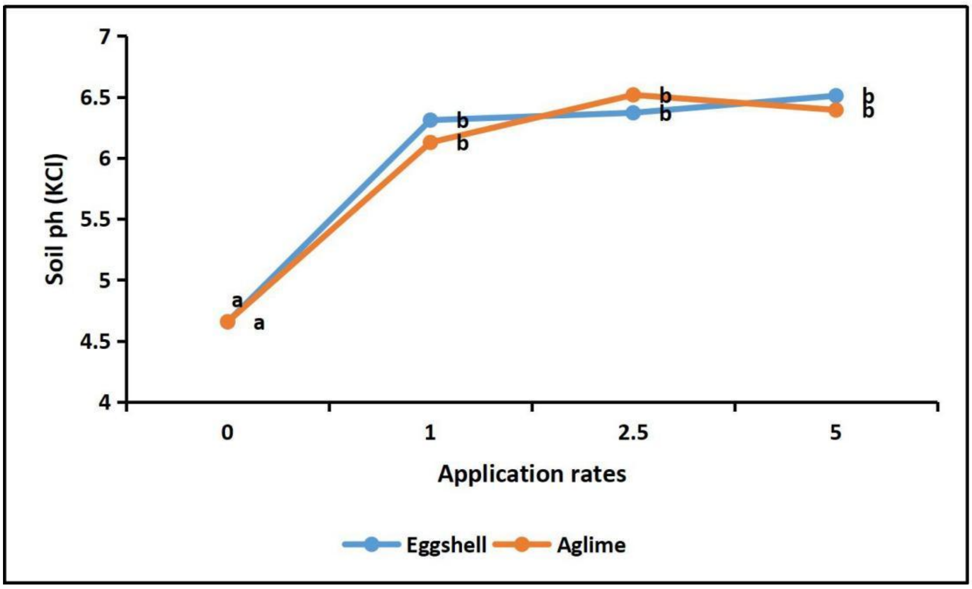

Figure 4.3: The effect of applied eggshells (A) and aglime (B) at four application rates (0, 1, 2.5, and 5 t/ha) on the soil pH (KCl) of sandy clay loam at day120 of the incubation study. Different letters indicate a significant difference (0.05) in soil pH between liming treatments (source and rates) using the Tukeys HSD test.

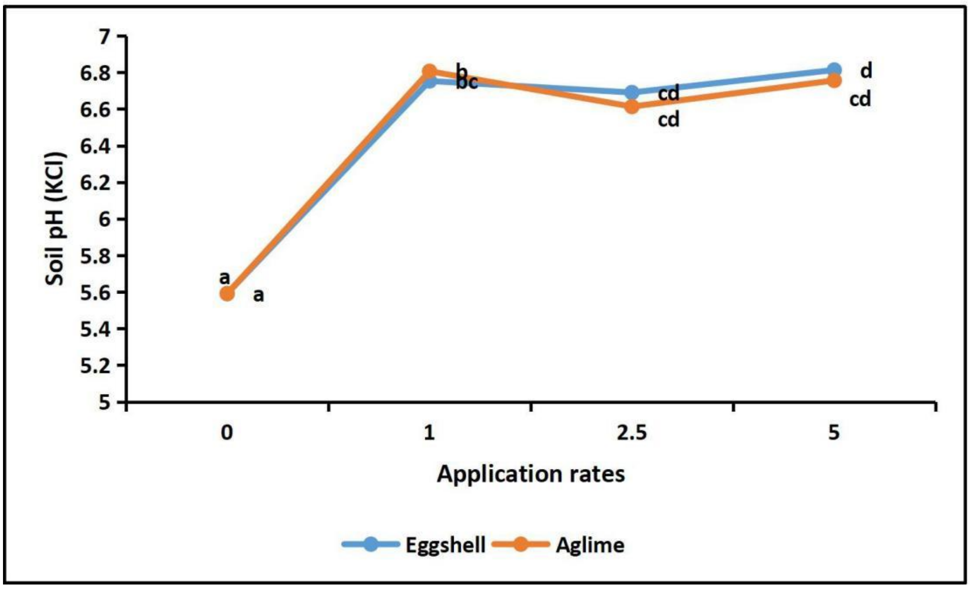

Figure 4.4: The effect of applied eggshells (A) and aglime (B) at four application rates (0, 1, 2.5, and 5 t/ha) on the soil pH (KCl) of sandy loam at day 120 for the incubation study. Different letters indicate a significant difference (0.05) in soil pH between liming treatments (source and rates) using the Tukeys HSD test.

4.1.2 Exchangeable acidity

The liming treatments (aglime and eggshell) significantly and completely neutralized the acidity of both soils within 7 days. The exchangeable acidity (EA) was reduced from an initial EA of 0.450 and 0.20 cmol/kg for sandy clay loam and sandy loam respectively to 0.05 cmol/kg for both soils. The effect of the liming treatments (aglime and eggshell) was not significantly different in neutralizing the soil acidity in both soils, moreover, the applied rates of 1, 2.5 and 5 t/ha were also not significantly different. All the applied rates were similar and therefore, appeared as one line in the graph, except for 5 t/ha application of eggshell in clay soil (Figure 4.5 & 4.6).

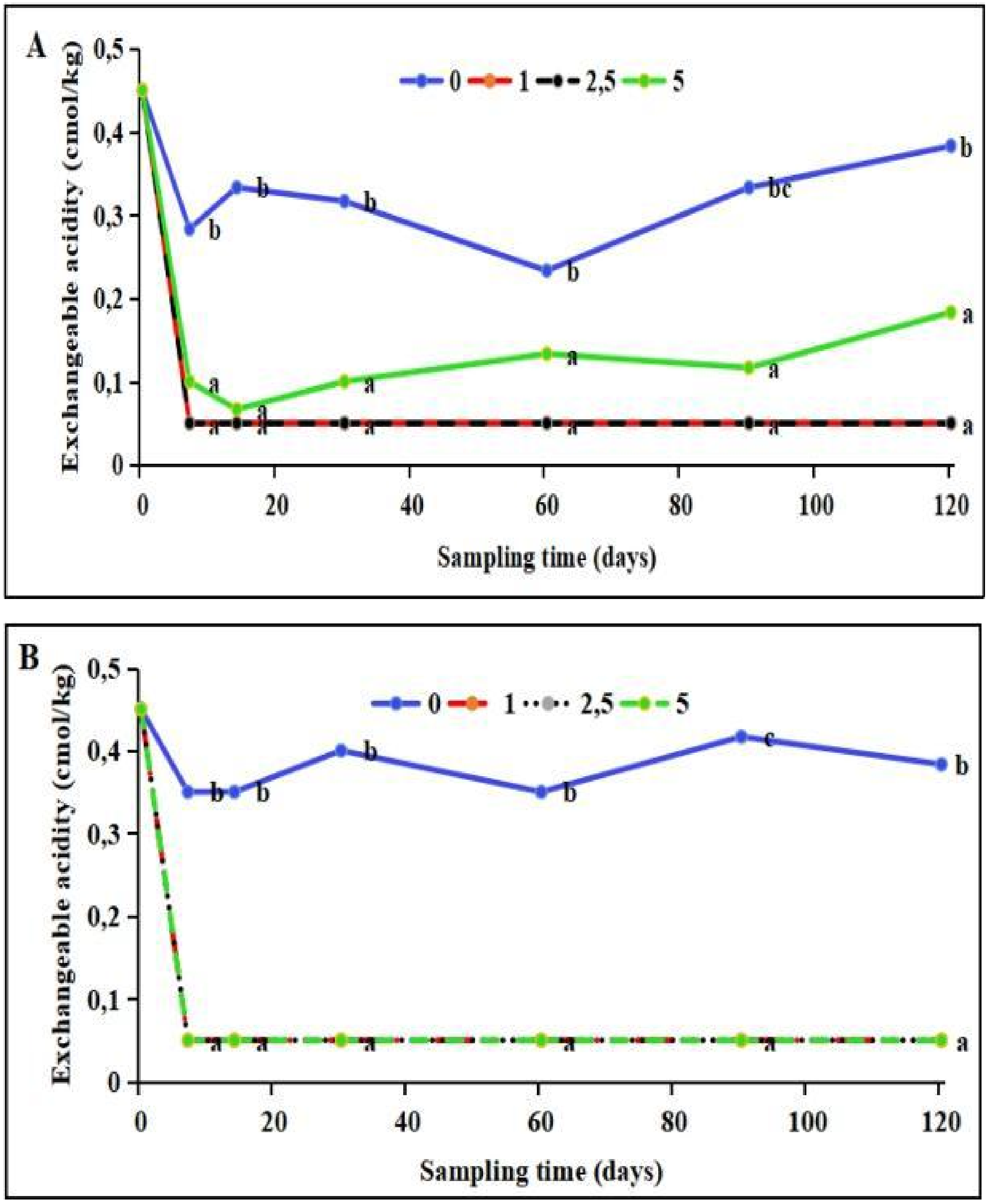

Figure 4.5: The effect of applied eggshells (A) and aglime (B) at four application rates (0, 1, 2.5, and 5 t/ha) on the exchangeable acidity of sandy clay loam over 120 days of the incubation study. Different letters indicate a significant difference (0.05) in exchangeable acidity between liming treatments (source and rates) for each sampling day using the Tukeys HSD test.

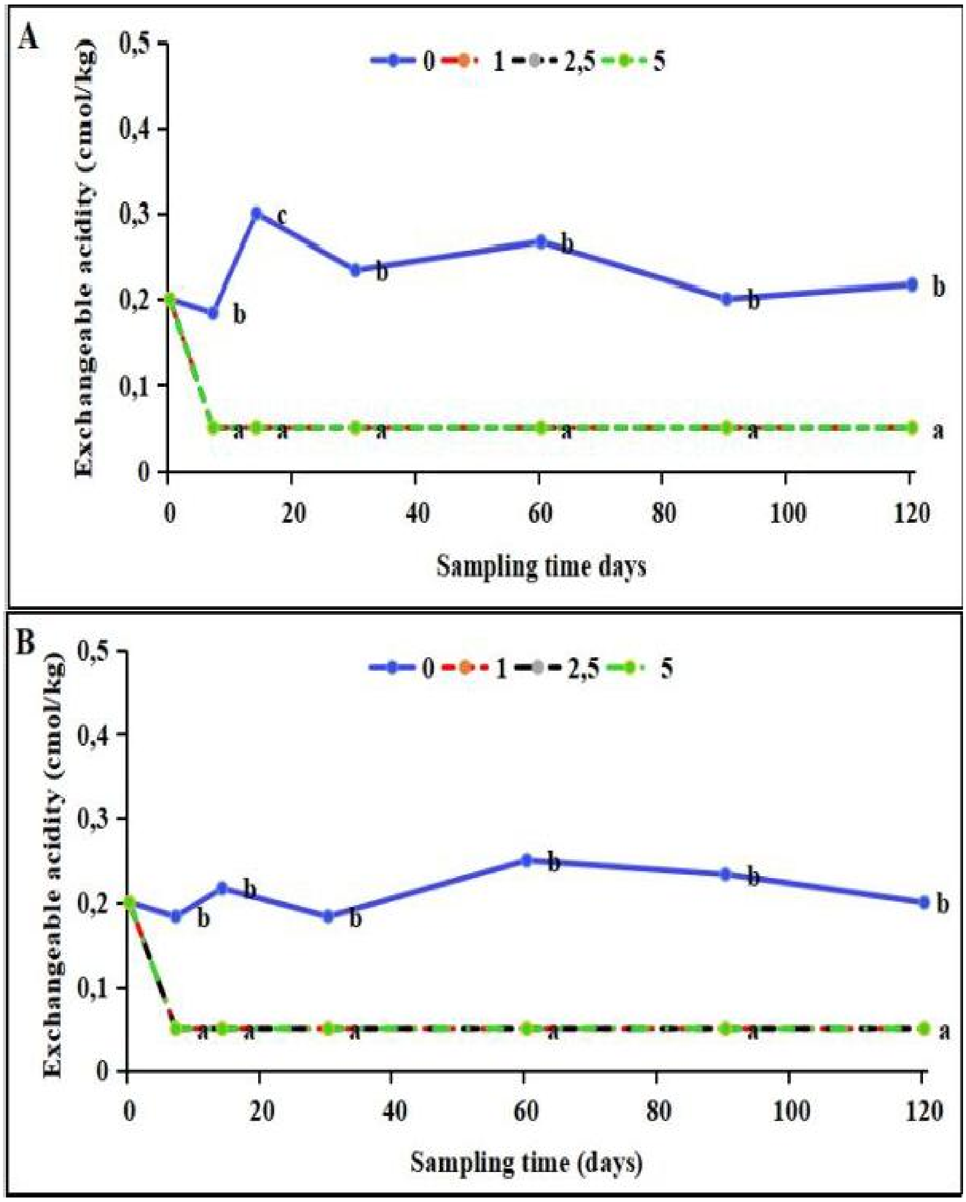

Figure 4.6: The effect of applied eggshells (A) and aglime (B) at four application rates (0, 1, 2.5, and 5 t/ha) on the exchangeable acidity of sandy loam over 120 days of the incubation study. Different letters indicate a significant difference (0.05) in exchangeable acidity between liming treatments (source and rates) for each sampling day using the Tukeys HSD test.

After 120 days, the exchangeable acidity under the application of eggshells and aglime in both the soils was significantly lower than the controls at all application rates, moreover, there was no significant difference between the two lime sources at all application rates (Figure 4.7 and 4.8).

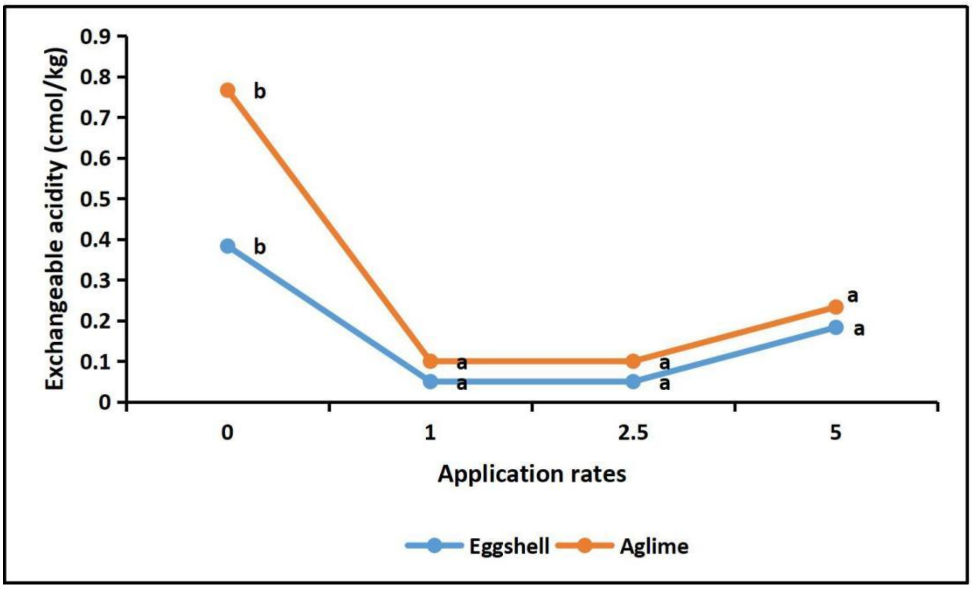

Figure 4.7: The effect of applied eggshells (A) and aglime (B) at four application rates (0, 1, 2.5, and 5 t/ha) on the exchangeable acidity of sandy clay loam at day 120 of the incubation study. Different letters indicate a significant difference (0.05) in exchangeable acidity between liming treatments (source and rates) using the Tukeys HSD test.

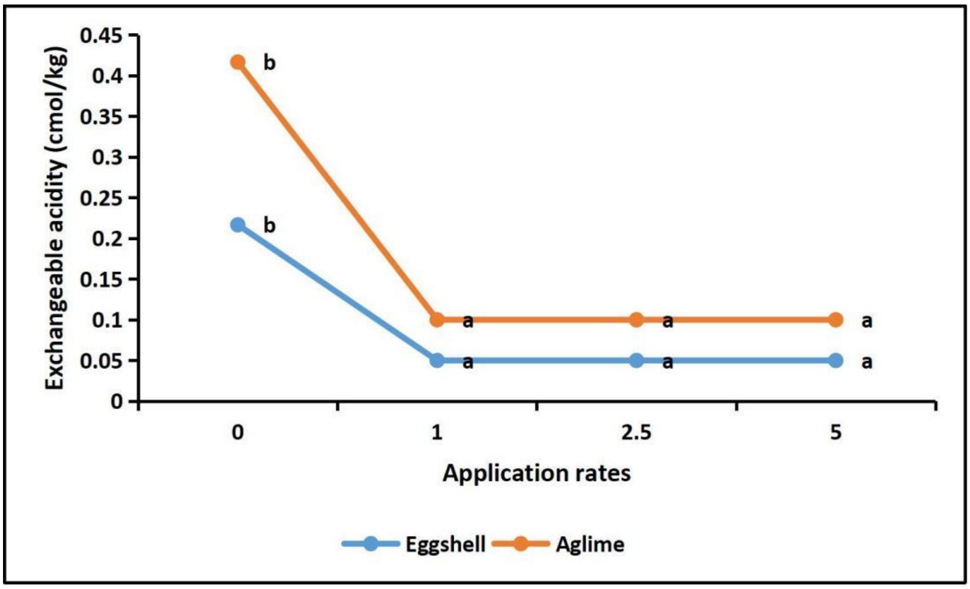

Figure 4.8: The effect of applied eggshells (A) and aglime (B) at four application rates (0, 1, 2.5, and 5 t/ha) on the exchangeable acidity of sandy loam at day 120 of the incubation study. Different letters indicate a significant difference (0.05) in exchangeable acidity between liming treatments (source and rates) using the Tukeys HSD test.

4.1.3 Plant-available phosphorus

The application of both eggshell and aglime did not significantly increase the plant-available phosphorus in comparison to the control for all application rates in sandy clay loam soil, except for 5 t/ha application of aglime treatment at days 60 and 90 (Figure 4.9). Similarly, the application of eggshell and aglime in sandy loam soil did not significantly increase the plant-available phosphorus in comparison to the control for all application rates, except for 2.5 t/ha application of eggshell at days 30, 90 and 120 and 5 t/ha application of aglime from day 14 to 120 (Figure 4.10). The liming source did not significantly affect the plant-available phosphorus at each application rate in both the soils. Moreover, the application rates of both the liming materials did not significantly affect the plant-available phosphorus in both soils.

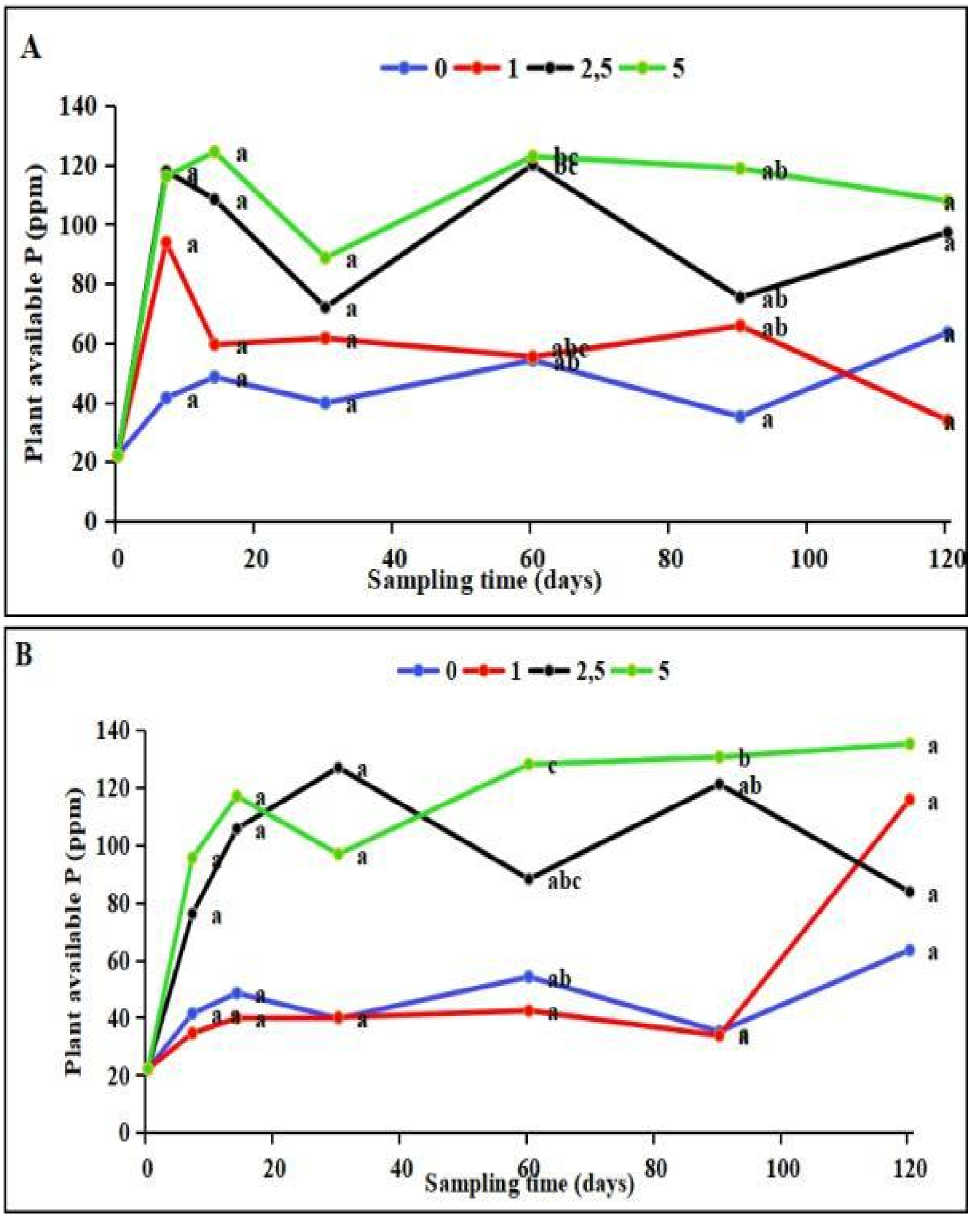

Figure 4.9: The effect of applied eggshells (A) and aglime (B) at four application rates (0, 1, 2.5, and 5 t/ha) on plant-available phosphorus in a sandy clay loam over 120 days of the incubation study. Different letters indicate a significant difference (0.05) in plant-available phosphorus between liming treatments (source and rates) for each sampling day using the Tukeys HSD test.

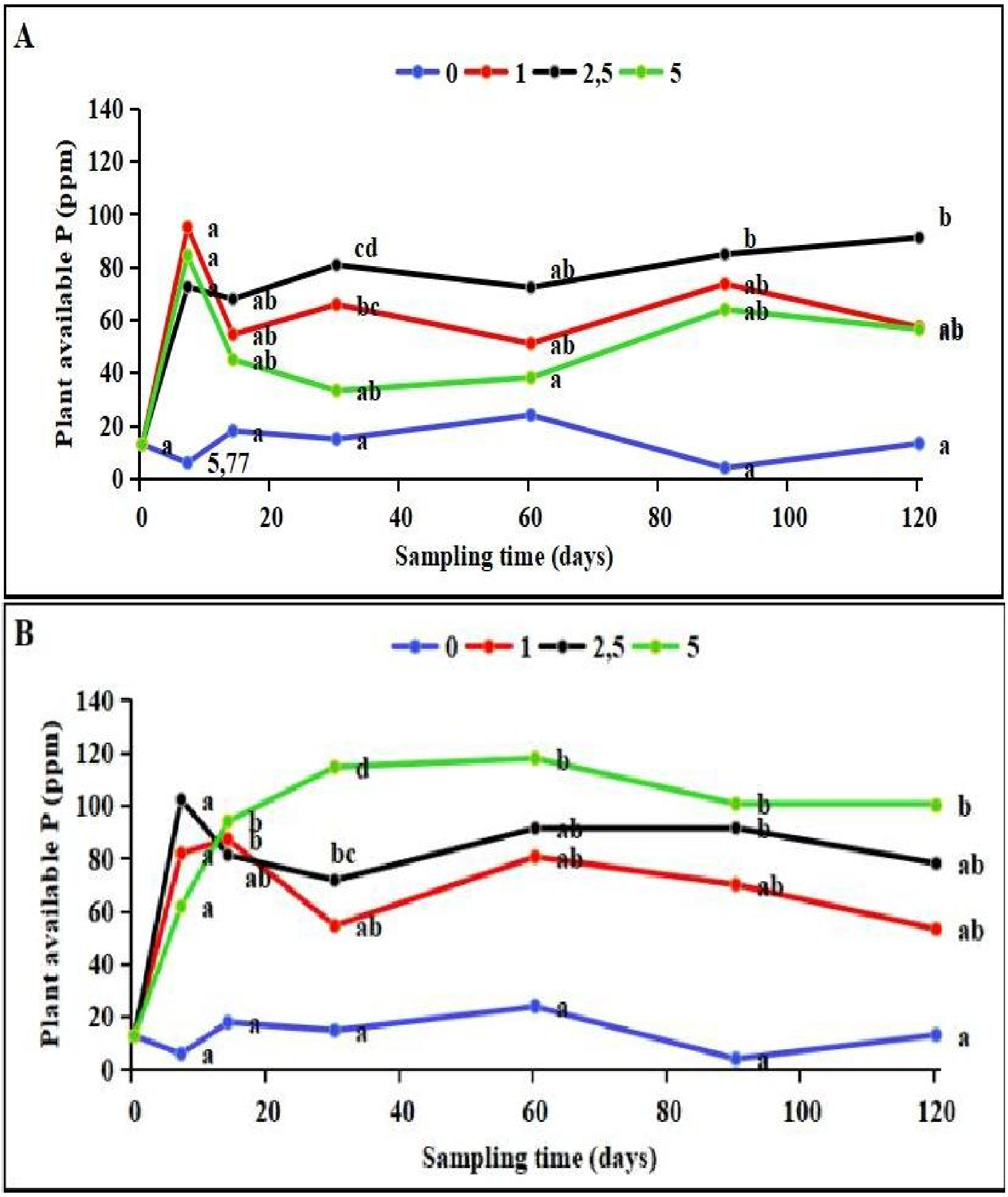

Figure 4.10: The effect of applied eggshells (A) and aglime (B) at four application rates (0, 1, 2.5, and 5 t/ha) on plant-available phosphorus in a sandy loam over 120 days of the incubation study. Different letters indicate a significant difference (0.05) in plant-available phosphorus between liming treatments (source and rates) for each sampling day using the Tukeys HSD test.

After 120 days, there was no significant difference in the plant-available phosphorus between all the application rates in both the soils, except the 5 t/ha application of aglime in sandy loam soil, which was significantly higher than the 0 t/ha application rate (Figure 4.11 and 4.12).

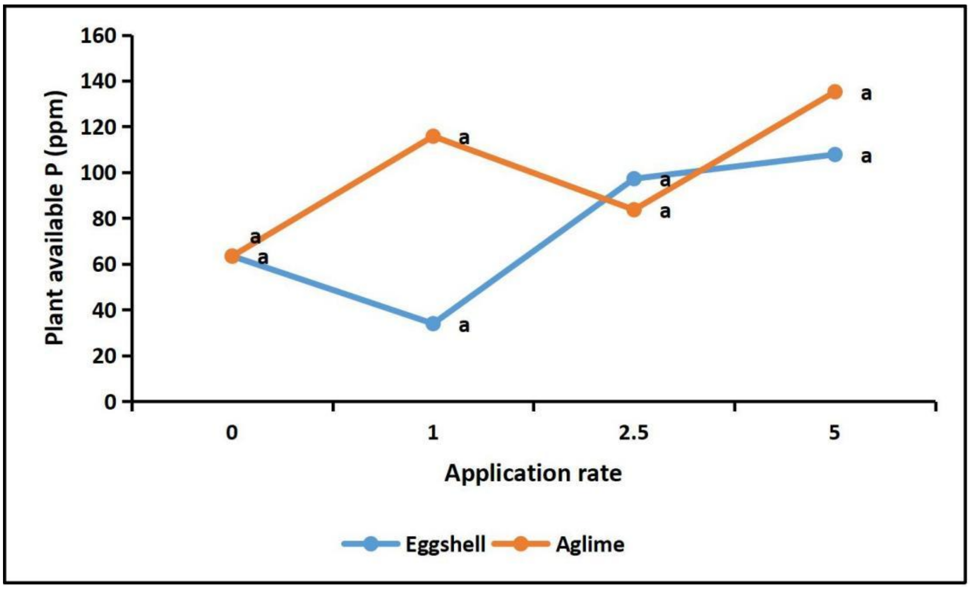

Figure 4.11: The effect of applied eggshells (A) and aglime (B) at four application rates (0, 1, 2.5, and 5 t/ha) on plant-available phosphorus in a sandy clay loam at day 120 of the incubation study. Different letters indicate a significant difference (0.05) in plant-available phosphorus between liming treatments (source and rates) using the Tukeys HSD test.

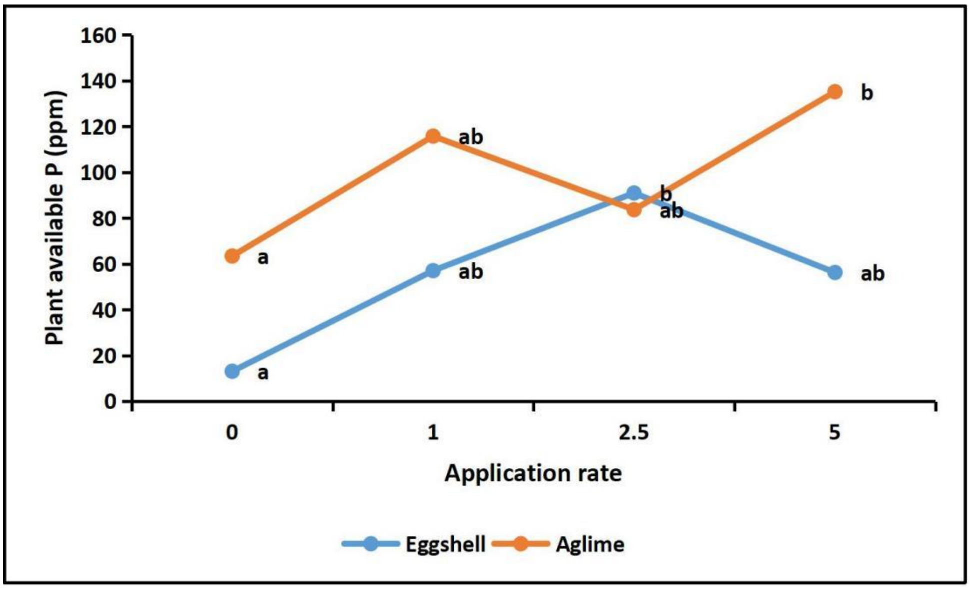

Figure 4.12: The effect of applied eggshells (A) and aglime (B) at four application rates (0, 1, 2.5, and 5 t/ha) on plant-available phosphorus in a sandy loam at day120 of the incubation study. Different letters indicate a significant difference (0.05) in plant-available phosphorus between liming treatments (source and rates) using the Tukeys HSD test.

4.2 FIELD EXPERIMENT

4.2.1 Soil pH

The pH of the soils under the application of eggshell & aglime was significantly higher than their respective controls at the end of the pot experiment (Figure 4.13). The soil pH increased in all the pots from the initial pH of 4.52 and 5.23 for sandy clay loam and sandy loam soil respectively, even for the controls. This was unexpected for the controls since they had not received any liming material, suggesting that there was another factor other than the added liming materials, which increased the soil pH. Although the applied treatments (eggshell and aglime) increased the soil pH significantly higher than the controls/rate 0, there was no significant difference between the two treatments (aglime and eggshell) at all application rates in increasing the soil pH, moreover, there was no significant difference between the applied rates (1. 2.5 & 5t/ha) in increasing the soil pH.

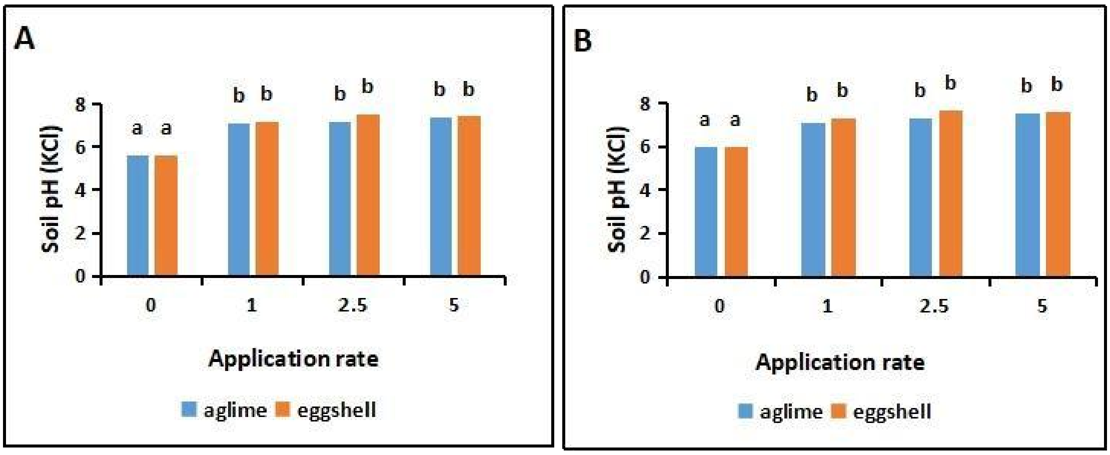

Figure 4.13: The effect of applied eggshells (orange) and aglime (blue) at four application rates (0, 1, 2.5, and 5 t/ha) on the soil pH (KCl) of sandy clay loam (A) and sandy loam (B) soil after 120 days of the pot trial. Different letters indicate a significant difference (0.05) in soil pH between the treatments (soil, liming source and rate) using the Tukeys HSD test.

4.2.2 Plant-available phosphorus

The application of both eggshells and aglime did not significantly increase the plant-available phosphorus in comparison to the control for all application rates in both soils, except for the 5 t/ha application of eggshell in sandy clay loam (Figure 4.14). As well, the liming source did not significantly affect the plant-available phosphorus at each application rate in both soils. Additionally, the application rates of both liming materials did not significantly affect the plant-available phosphorus in both soils.

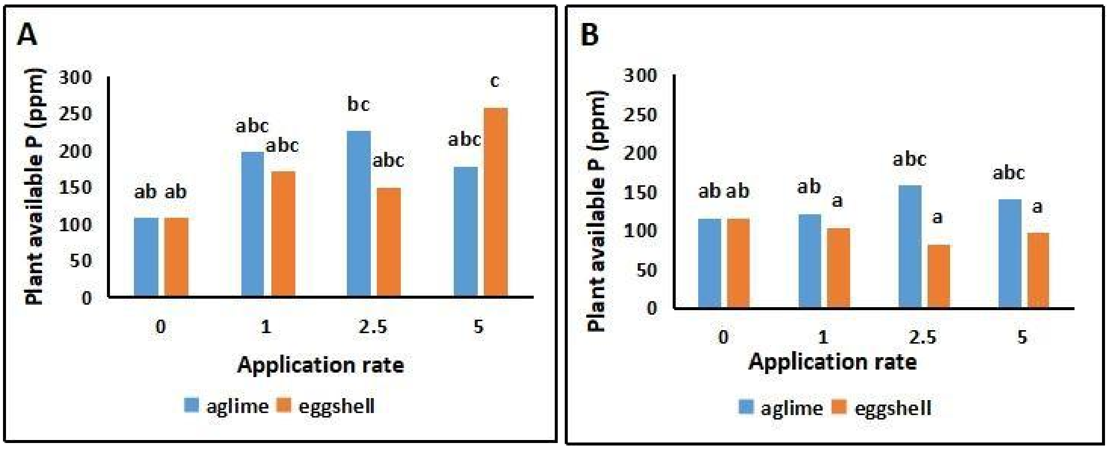

Figure 4.14: The effect of applied eggshells (orange) and aglime (blue) at four application rates (0, 1, 2.5, and 5 t/ha) on plant-available phosphorus in a sandy clay loam (A) and sandy loam soil (B) after 120 days of the pot trial. Different letters indicate a significant difference (0.05) in the plant-available phosphorus between the treatments (soil, liming source and rate) using the Tukeys HSD test.

4.2.3 Dry weight

It was observed that the Swiss chard growing at the 0 t/ha (control) in the sandy clay loam soil showed poor and stunted growth throughout the growing season while Swiss chard growing at the 0 t/ha (control) in the sandy loam soil did not exhibit poor and stunted growth (Figure 4.15 & 4.16).

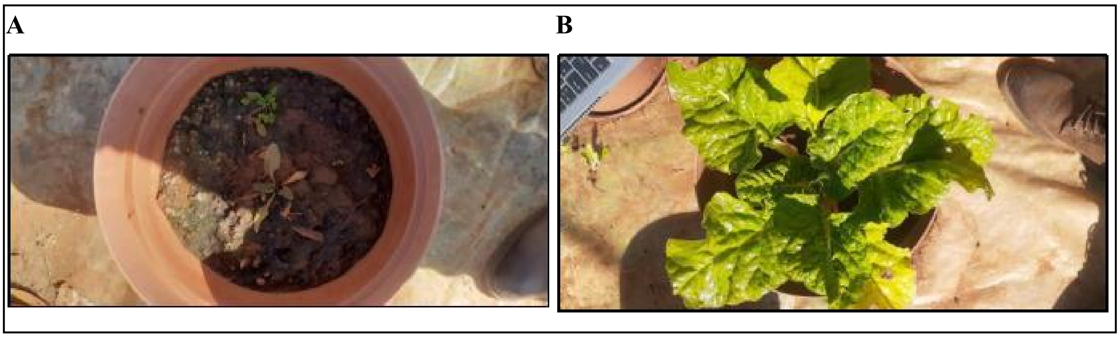

Figure 4.15: The control plant (A) in sandy clay loam soil compared to the eggshell treated plant (B) in sandy clay loam soil after 120 days of pot trial.

Figure 4.16: The effect of applied liming material (eggshell and aglime) at four application rates (0, 1, 2.5, & 5 t/ha) on the growth of Swiss Chard in a sandy clay loam and a sandy loam soils. The pots that appear to have no plants inside are the controls for sandy clay loam soil.

The application of both eggshells and aglime did not significantly increase the Swiss chard dry weight in comparison to the control for all application rates in both soils, except for the 1.0 t/ha application of eggshells in the sandy clay loam (Figure 4.17). As well, the liming source did not significantly affect the Swiss chard dry weight at each application rate in both soils. Additionally, the application rates of both liming materials did not significantly affect the Swiss chard dry weight in both soils.

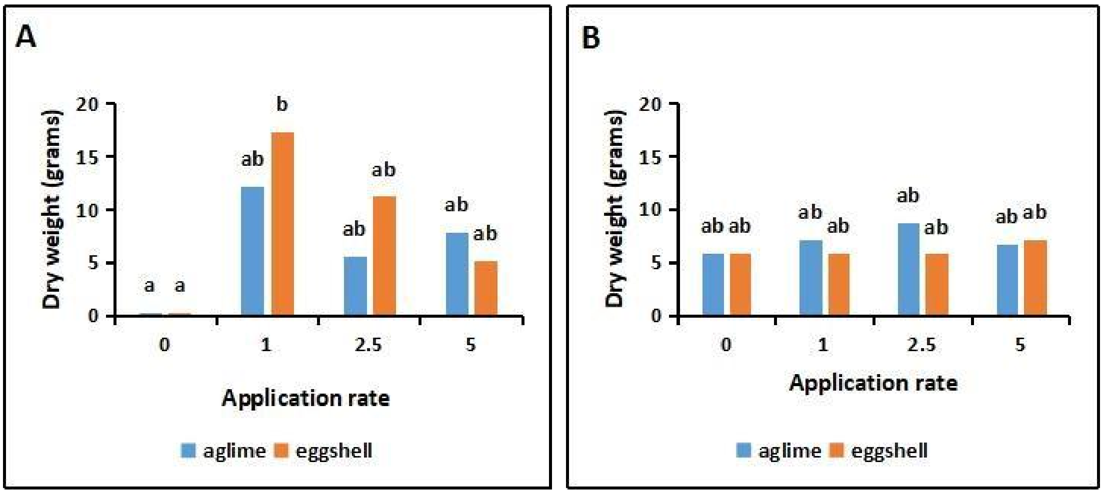

Figure 4.17: The effect of applied eggshells (orange) and aglime (blue) at four application rates (0, 1, 2.5, and 5 t/ha) on the yield/dry matter of Swiss chard in sandy clay loam (A) and sandy loam soil (B) after 120 days of the pot trial. Different letters indicate a significant difference (0.05) in dry weight between the treatments (soil, liming source and rate) using the Tukeys HSD test.

CHAPTER 5: DISCUSSION

The primary objective of this study was to evaluate the liming potential of ground eggshells on two soils of different textures using an incubation and pot experiment. The liming potential of any material is evaluated by its ability to change the soil pH in acidic soil.

The soil pH results in both studies (incubation and pot trial) revealed a significant increase in soil pH under the application of ground eggshell and aglime in both soils, but there was no significant difference between the two applied lime sources. The increase in soil pH in the incubation study occurred within 7 days, which was quicker than what other related studies reported (Akinmutimi and Agwu, 2014; Holmes *et al*., 2011). Grinding the liming materials could have increased the surface area of the materials and subsequently, a faster soil reaction. Mitchel (2005) reported a significant increase in soil pH under the application of ground eggshells for 2 days in a sandy loam soil with an initial pH of 4.9, which was similar to one of this study's soils. Akinmutini and Agwu (2014) and Holmes *et al*. (2011) analyzed their first soil pH after 2 weeks and 6 months respectively, and this could have created a possible missing gap whereby the soil pH could have increased earlier than when the first analysis was done. Similarly, the soil pH for the incubation study could have increased earlier than when the first analysis was done. It is therefore, essential for future studies to analyze their soil pH daily for the first week.

Burley and Vedehra (1989) reported that eggshells and aglime have similar chemical compositions. This was supported by the XRD diffraction patterns of calcite in eggshells and aglime in this study (Figure 3.1). Since both the liming materials contained similar chemical composition, it is feasible that there was no significant difference between the two liming sources. The process of acid neutralization by liming is essentially the displacement of hydrogen ions by calcium, therefore, liming materials with similar calcium carbonate equivalent (CCE) and fineness are inclined to have similar effective neutralizing value (ENV). Earlier studies reported that eggshells were an effective liming material; however, they have a slow dissolution rate as compared to aglime (Holmes *et al*., 2011). This was later disputed by recent studies that reported a similar dissolution rate of eggshells and agilme (Akinmutimi and Agwu, 2014) and in some instances, quicker than aglime (Mitchel, 2005).

However, Mitchel (2005) further highlighted that eggshells are only effective when they are finely ground.

The soil pH in the pot experiment increased in the 0 t/ha rates (controls), which was unexpected since they had not received any liming material. This suggests that there was another factor other than the applied liming material, which increased the soil pH. Mengel, (1994) reported that irrigation water can contain high amounts of calcium, magnesium and bicarbonates, which can eventually replace the hydrogen ions in the soil and increase the soil pH. Moreover, there are reported cases of root-mediated pH changes, which increase the pH in the rhizosphere (Marschner *et al*., 1986). However, this was not investigated in the study.

The process of acid neutralization involves the displacement of hydrogen ions by an equivalence of calcium. Therefore, different quantities of lime per given area may neutralize the same acidity given that all the liming materials had sufficient calcium present to neutralize acidity. The application rates of both liming materials did not significantly affect the soil pH in both soils, and this may be because all the applied rates had sufficient calcium to neutralize the acidity that was in the soils. Eggshells and aglime are composed of $CaCO_3$, which is not soluble in water and dissolves in acidic conditions and not alkaline (acid base reaction). Therefore, as the soil pH increases, the dissolution rate of the liming material is reduced until an equilibrium pH is reached. Mitchel (2005) reported that the dissolution rate of any liming material will stop at a pH of 6.8 and eventually its subsequent effects. Therefore, the different quantities of lime may similarly increase the soil pH provided that an equilibrium is reached. However, higher rates have the advantage of continuous reaction, which can stabilize soil pH for a longer period than lower rates since excess lime may always be released to react with the acidity as the pH drops.

The soil pH for the incubation experiment under the application of the two lime sources quickly increased in the sandy clay loam and plateaued after 7 days, whereas in the sandy loam soil, it plateaued after 14 days. The opposite was expected since sandy clay loam soils have a higher buffering capacity than sandy loam soils. However, lime requires water for soil acid neutralization; therefore, lime will react more quickly in soils with a higher water holding capacity than in soils with less water holding capacity. This might have caused a quicker reaction in the sandy clay loam since it has a higher water holding capacity than the sandy loam soil. The final soil pH of the sandy loam in the incubation experiment was slightly higher than that of the sandy clay loam soil. This may be because sandy clay loam soils have a higher buffering capacity as compared to sandy loam soil.

The applied liming materials were effective in raising the soil pH, moreover, they were able to neutralize all the acidity in the soil. There are two types of acidity in the soil, active and reserve acidity. The soil pH measures the active acidity and may therefore, not measure all the hydrogen ions in the soil since some hydrogen ions are bound in the soil particles and not dissolved. However, these hydrogen ions can be determined by measuring the exchangeable acidity, which by definition is the measure of hydrogen ions retained or fixed on soil colloids after active acidity is measured. The exchangeable acidity results revealed that the application of both eggshells and aglime significantly neutralized the acidity in the soil in comparison to the control for all application rates in both the soils. This suggests that all the application rates had sufficient calcite to neutralize both active and reserve acidity.

The significance of the soil pH is that it affects the amount of chemicals and nutrients that are soluble in water, which subsequently influences the amount of nutrients available to the plant. It is therefore, fundamentally important to regularly test for soil pH.

Phosphorus is one of the essential nutrients that are required for plant growth and is required in large quantities since it is a macro-nutrient. The availability of phosphorus is largely influenced by soil pH, organic matter and exchangeable and soluble Al, Fe and Ca. The availability of phosphorus is at its maximum between the pH range of 5.5 and 7 (Havlin *et al*., 2005). However, when the soil becomes acidic, P is fixed by Al and Fe. Similarly, in alkaline soils, P is fixed by Ca and becomes less available. The application of eggshell and aglime appeared to increase the plant-available phosphorus but the increase was not significantly different compared to the control at all application rates at 0.5% level. The apparent increase can be related to the effectof the soil pH as affected by both liming sources. The plant-available phosphorus in the sandy loam at 0 t/ha (control) rate was below the healthy level of soil phosphorus, which is 25 ppm (Havlin *et al*., 2005) whereas the 0 t/ha (control) rate in the sandy clay loam was above 25 ppm. Phosphorus retention by soils with more clay has been shown to adsorb phosphorus easily (Havlin *et al*., 2005) since clay particles have a larger surface area and possible higher potential anion adsorption capacity (AEC) for phosphorus adsorption.

The concentration of hydrogen ions in the soil regulates the entire chemistry of plant nutrient colloidal solutions. At certain pH levels, multiple stresses such as nutrient imbalance, hydrogen ion toxicity, toxicities and deficiencies are induced in plants (Neumann and Romheld, 2002). The growth of Swiss chard at the 0 t/ha in sandy clay loam showed poor and stunted growth throughout the study while its growth at 0 t/ha in sandy loam did not exhibit poor and stunted growth. This may be a result of the initial soil pH of 4.2 in sandy clay loam, which was lower than the pH suitable for most vegetable crops, which is between 5.5 and 7. The initial soil pH of sandy loam was 5.23, which was near the optimum soil pH for most plant growth. Soil acidity is usually associated with poor plant growth since it decreases the availability of plant nutrients, such as molybdenum and phosphorus, and increases the availability of some elements to toxic levels such as Al and Mn (Gupta *et al.*, 2013). Although the final soil pH level of sandy clay loam was increased, the increase could have taken a longer period as compared to the soils that were treated with eggshells and aglime, which proved to be fast reactive from the incubation study and other related studies.

The application of both eggshells and aglime were not significantly different in increasing the growth of Swiss chard. This is because both the applied treatments have similar chemical compositions, which subsequently resulted in similar effects in the soil. Both lime sources increased the soil pH significantly the same as compared to the controls, and therefore, the nutrient availability under the application of eggshell and aglime would be similar per given soil and eventually, the associated plant growth. Since the applied rates of both liming materials were not significantly different in increasing the soil pH, their influence on the soil is likely to be similar and eventually plant growth.

CONCLUSION

This study demonstrated that both ground eggshell and aglime are effective liming materials and are not significantly different in increasing the soil pH. This implies that ground eggshells can be used with aglime or as a substitute of aglime. The recommended application rate that was used in the study was 5 t/ ha; however, according to the results, there was no significant difference in soil pH between all the application rates. This suggests that the economical application rate should be 1 t/ha. The fast reactive nature of the applied lime sources may be attributed to the initial grinding of the liming materials. Therefore, to obtain similar results or a quick reaction from the liming materials, it is essential to grind them before application.

The findings of this study are limited to particles less than 2 mm without the knowledge of particle size distribution. It is therefore, recommended for future studies to investigate the effect of different particle sizes of ground eggshells on its dissolution rate.

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APPENDICES

Appendix 1: Analysis of variance for soil pH incubation study on sandy loam soil for day 7, 14, 30, 60, 90 and 120.

Variate: Day7

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2		0.10136	0.05068	1.19	
Rep.*Units* stratum						
Source	1		0.00743	0.00743	0.17	0.682
Rate	3		12.30340	4.10113	96.38	<.001
Source.Rate	3		0.02019	0.00673	0.16	0.923
Residual	14	(144)	0.59572	0.04255		

Total 23 (144) 2.38133

Variate: Day14

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2		1.05905	0.52953	6.65	
Rep.*Units* stratum						
Source	1		0.38366	0.38366	4.82	0.046
Rate	3		16.49629	5.49876	69.05	<.001
Source.Rate	3		0.83860	0.27953	3.51	0.044
Residual	14	(144)	1.11485	0.07963		

Total 23 (144) 3.81180

Variate: Day30

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2		0.36914	0.18457	11.37	
Rep.*Units* stratum						
Source	1		0.00186	0.00186	0.11	0.740
Rate	3		27.20292	9.06764	558.55	<.001
Source.Rate	3		0.41785	0.13928	8.58	0.002
Residual	14	(144)	0.22728	0.01623		

Total 23 (144) 4.23553

Variate: Day60

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2		0.42273	0.21137	7.31	
Rep.*Units* stratum						
Source	1		0.01283	0.01283	0.44	0.516
Rate	3		24.95192	8.31731	287.67	<.001
Source.Rate	3		0.60205	0.20068	6.94	0.004
Residual	14	(144)	0.40478	0.02891		
Total	23	(144)	4.12790			

Variate: Day90

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2		0.359011	0.179506	24.21	
Rep.*Units* stratum						
Source	1		0.026188	0.026188	3.53	0.081
Rate	3		32.824195	10.941398	1475.73	<.001
Source.Rate	3		0.181222	0.060407	8.15	0.002
Residual	14	(144)	0.103799	0.007414		

Total 23 (144) 4.885133

Variate: Day120

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Rep stratum	2		0.19106	0.09553	7.89	
Rep.*Units* stratum						
Source	1		0.01676	0.01676	1.38	0.259
Rate	3		41.95911	13.98637	1154.64	<.001
Source.Rate	3		0.10824	0.03608	2.98	0.068
Residual	14	(144)	0.16958	0.01211		

Total 23 (144) 6.22313

Appendix 2: Analysis of variance for the soil pH in the incubation study on sandy clay loam soil for day 7, 14, 30, 60 and 120.

Variate: Day7

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.18697	0.09349	3.29	
Rep.*Units* stratum					
Source	1	0.11070	0.11070	3.90	0.068
Rate	3	6.71095	2.23698	78.80	<.001
Source.Rate	3	0.21731	0.07244	2.55	0.097
Residual	14	0.39742	0.02839		
Total	23	7.62336			

Variate: Day14

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.48131	0.24065	3.52	
Rep.*Units* stratum					
Source	1	0.12042	0.12042	1.76	0.206
Rate	3	9.86068	3.28689	48.11	<.001
Source.Rate	3	0.15202	0.05067	0.74	0.545
Residual	14	0.95656	0.06833		
Total	23	11.57098			

Variate: Day30

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.08311	0.04155	0.55	
Rep.*Units* stratum					
Source	1	0.20167	0.20167	2.66	0.125
Rate	3	12.62110	4.20703	55.40	<.001
Source.Rate	3	0.09477	0.03159	0.42	0.744
Residual	14	1.06309	0.07594		
Total	23	14.06373			

Variate: Day60

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.03541	0.01770	0.90	
Rep.*Units* stratum					
Source	1	0.06720	0.06720	3.43	0.085
Rate	3	13.37161	4.45720	227.36	<.001
Source.Rate	3	0.14241	0.04747	2.42	0.109
Residual	14	0.27446	0.01960		
Total	23	13.89110			

Variate: Day90

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.03663	0.01832	0.44	
Rep.*Units* stratum					
Source	1	0.04770	0.04770	1.15	0.302
Rate	3	11.44845	3.81615	91.93	<.001
Source.Rate	3	0.03195	0.01065	0.26	0.855
Residual	14	0.58117	0.04151		

Total 23 12.14590

Variate: Day120

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.00968	0.00484	0.11	
Rep.*Units* stratum					
Source	1	0.00882	0.00882	0.20	0.663
Rate	3	13.43722	4.47907	100.84	<.001
Source.Rate	3	0.09428	0.03143	0.71	0.563
Residual	14	0.62186	0.04442		

Total 23 14.17185

Appendix 3: Analysis of variance for exchangeable acidity for the incubation study on sandy loam soil for day 7, 14, 30, 60, 90 and 120.

Variate: Day7

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.0008333	0.0004167	2.33	
Rep.*Units* stratum					
Source	1	0.0000000	0.0000000	0.00	1.000
Rate	3	0.0800000	0.0266667	149.33	<.001
Source.Rate	3	0.0000000	0.0000000	0.00	1.000
Residual	14	0.0025000	0.0001786		
Total	23	0.0833333			

Variate: Day14

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.0014583	0.0007292	1.96	
Rep.*Units* stratum					
Source	1	0.0026042	0.0026042	7.00	0.019
Rate	3	0.1953125	0.0651042	175.00	<.001
Source.Rate	3	0.0078125	0.0026042	7.00	0.004
Residual	14	0.0052083	0.0003720		
Total	23	0.2123958			

Variate: Day30

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.0008333	0.0004167	0.47	
Rep.*Units* stratum					
Source	1	0.0009375	0.0009375	1.05	0.323
Rate	3	0.1128125	0.0376042	42.12	<.001
Source.Rate	3	0.0028125	0.0009375	1.05	0.401
Residual	14	0.0125000	0.0008929		
Total	23	0.1298958			

Variate: Day60

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.003958	0.001979	0.85	
Rep.*Units* stratum					
Source	1	0.000104	0.000104	0.04	0.836
Rate	3	0.195312	0.065104	27.87	<.001
Source.Rate	3	0.000313	0.000104	0.04	0.987
Residual	14	0.032708	0.002336		
Total	23	0.232396			

Variate: Day90

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.0008333	0.0004167	1.00	
Rep.*Units* stratum					
Source	1	0.0004167	0.0004167	1.00	0.334
Rate	3	0.1250000	0.0416667	100.00	<.001
Source.Rate	3	0.0012500	0.0004167	1.00	0.422
Residual	14	0.0058333	0.0004167		
Total	23	0.1333333			

Variate: Day120

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.0014583	0.0007292	1.96	
Rep.*Units* stratum					
Source	1	0.0001042	0.0001042	0.28	0.605
Rate	3	0.1128125	0.0376042	101.08	<.001
Source.Rate	3	0.0003125	0.0001042	0.28	0.839
Residual	14	0.0052083	0.0003720		
Total	23	0.1198958			

Appendix 4: Analysis of variance for exchangeable acidity for the incubation study on sandy clay loam soil for day 7, 14, 30, 60, 90 and 120.

Variate: Day7

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.010833	0.005417	1.49	
Rep.*Units* stratum					
Source	1	0.000104	0.000104	0.03	0.868
Rate	3	0.302813	0.100938	27.80	<.001
Source.Rate	3	0.010313	0.003438	0.95	0.445
Residual	14	0.050833	0.003631		
Total	23	0.374896			

Variate: Day14

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.004375	0.002188	1.28	
Rep.*Units* stratum					
Source	1	0.000000	0.000000	0.00	1.000
Rate	3	0.375833	0.125278	73.21	<.001
Source.Rate	3	0.000833	0.000278	0.16	0.920
Residual	14	0.023958	0.001711		

Total 23 0.405000

Variate: Day30

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.000208	0.000104	0.04	
Rep.*Units* stratum					
Source	1	0.000417	0.000417	0.14	0.713
Rate	3	0.407500	0.135833	45.87	<.001
Source.Rate	3	0.013750	0.004583	1.55	0.246
Residual	14	0.041458	0.002961		

Total 23 0.463333

Variate: Day60

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.006458	0.003229	0.73	
Rep.*Units* stratum					
Source	1	0.000417	0.000417	0.09	0.763
Rate	3	0.240417	0.080139	18.13	<.001
Source.Rate	3	0.030417	0.010139	2.29	0.123
Residual	14	0.061875	0.004420		

Total 23 0.339583

Variate: Day90

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.000833	0.000417	0.06	
Rep.*Units* stratum					
Source	1	0.000104	0.000104	0.01	0.905
Rate	3	0.447813	0.149271	21.07	<.001
Source.Rate	3	0.016979	0.005660	0.80	0.515
Residual	14	0.099167	0.007083		
Total	23	0.564896			

Variate: Day120

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.023125	0.011563	1.67	
Rep.*Units* stratum					
Source	1	0.006667	0.006667	0.96	0.343
Rate	3	0.453333	0.151111	21.84	<.001
Source.Rate	3	0.020000	0.006667	0.96	0.437
Residual	14	0.096875	0.006920		
Total	23	0.600000			

Appendix 5: Analysis of variance for plant-available phosphorus for the incubation study on sandy loam soil for day 7, 14, 30, 60, 90 and 120.

Variate: Day7

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	1842.	921.	0.49	
Rep.*Units* stratum					
Source	1	13.	13.	0.01	0.936
Rate	3	27616.	9205.	4.92	0.015
Source.Rate	3	2352.	784.	0.42	0.742
Residual	14	26202.	1872.		
Total	23	58024.			

Variate: Day14

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	739.7	369.8	0.73	
Rep.*Units* stratum					
Source	1	3401.9	3401.9	6.70	0.021

Rate	3	13046.6	4348.9	8.56	0.002
Source.Rate	3	2082.0	694.0	1.37	0.294
Residual	14	7113.7	508.1		
Total	23	26383.9			

Variate: Day30

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	709.3	354.7	1.88	
Rep.*Units* stratum					
Source	1	1401.6	1401.6	7.42	0.016
Rate	3	14624.0	4874.7	25.81	<.001
Source.Rate	3	8844.4	2948.1	15.61	<.001
Residual	14	2643.9	188.8		
Total	23	28223.2			

Variate: Day60

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	1563.1	781.6	1.28	
Rep.*Units* stratum					
Source	1	6187.9	6187.9	10.12	0.007
Rate	3	12659.7	4219.9	6.90	0.004
Source.Rate	3	5218.2	1739.4	2.85	0.076
Residual	14	8558.4	611.3		

Total 23 34187.4

Variate: Day90

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	176.9	88.5	0.15	
Rep.*Units* stratum					
Source	1	602.8	602.8	1.03	0.327
Rate	3	27310.9	9103.6	15.59	<.001
Source.Rate	3	1513.0	504.3	0.86	0.483
Residual	14	8175.7	584.0		

Total 23 37779.3

Variate: Day120

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	3391.3	1695.6	2.40	
Rep.*Units* stratum					

Source	1	267.9	267.9	0.38	0.548
Rate	3	18791.7	6263.9	8.85	0.002
Source.Rate	3	2870.5	956.8	1.35	0.298
Residual	14	9905.7	707.6		
Total	23	35227.1			

Appendix 6: Analysis of variance for plant-available phosphorus for the incubation study on sandy clay loam soil for day 7, 14, 30, 60, 90 and 120.

Variate: Day7

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	2839.	1420.	0.72	
Rep.*Units* stratum					
Source	1	5543.	5543.	2.79	0.117
Rate	3	15958.	5319.	2.68	0.087
Source.Rate	3	2986.	995.	0.50	0.687
Residual	14	27763.	1983.		
Total	23	55089.			

Variate: Day14

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	1744.	872.	0.85	
Rep.*Units* stratum					
Source	1	327.	327.	0.32	0.580
Rate	3	25736.	8579.	8.41	0.002
Source.Rate	3	342.	114.	0.11	0.952
Residual	14	14286.	1020.		
Total	23	42435.			

Variate: Day30

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	559.	280.	0.22	
Rep.*Units* stratum					
Source	1	658.	658.	0.53	0.480
Rate	3	15999.	5333.	4.28	0.024
Source.Rate	3	4681.	1560.	1.25	0.329
Residual	14	17461.	1247.		
Total	23	39358.			

Variate: Day60

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.

Rep stratum	2	1214.8	607.4	0.93	
Rep.*Units* stratum					
Source	1	579.0	579.0	0.88	0.364
Rate	3	25485.3	8495.1	12.94	<.001
Source.Rate	3	1231.1	410.4	0.63	0.611
Residual	14	9191.4	656.5		
Total	23	37701.6			

Variate: Day90

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	5316.	2658.	2.43	
Rep.*Units* stratum					
Source	1	250.	250.	0.23	0.640
Rate	3	31336.	10445.	9.56	0.001
Source.Rate	3	4659.	1553.	1.42	0.278
Residual	14	15295.	1093.		
Total	23	56857.			

Variate: Day120

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	1429.	715.	0.22	
Rep.*Units* stratum					
Source	1	3438.	3438.	1.04	0.326
Rate	3	11435.	3812.	1.15	0.364
Source.Rate	3	8024.	2675.	0.81	0.511
Residual	14	46459.	3319.		
Total	23	70785.			

Appendix 7: Analysis of variance for soil pH for the greenhouse study.

Variate: pH

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.31240	0.15620	2.43	
Rep.*Units* stratum					
Soil	1	0.52292	0.52292	8.14	0.008
Source	1	0.23660	0.23660	3.68	0.065
Rate	3	23.01786	7.67262	119.40	<.001
Soil.Source	1	0.01235	0.01235	0.19	0.664
Soil.Rate	3	0.15902	0.05301	0.82	0.491
Source.Rate	3	0.17394	0.05798	0.90	0.452
Soil.Source.Rate	3	0.01202	0.00401	0.06	0.979
Residual	30	1.92773	0.06426		

Total	47	26.37485

Appendix 8: Analysis of variance for the plant-available phosphorus for the greenhouse study.

Variate: P

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	600.	300.	0.19	
Rep.*Units* stratum					
Soil	1	41938.	41938.	26.81	<.001
Source	1	4967.	4967.	3.18	0.085
Rate	3	21705.	7235.	4.63	0.009
Soil.Source	1	2527.	2527.	1.62	0.213
Soil.Rate	3	18431.	6144.	3.93	0.018
Source.Rate	3	14907.	4969.	3.18	0.038
Soil.Source.Rate	3	8956.	2985.	1.91	0.149
Residual	30	46924.	1564.		
Total	47	160957.			

Appendix 9: Analysis of variance for the plant dry weight in the greenhouse study.

Variate: Dry_weight

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	82.61	41.30	1.82	
Rep.*Units* stratum					
Soil	1	9.39	9.39	0.41	0.525
Source	1	3.55	3.55	0.16	0.695
Rate	3	351.68	117.23	5.17	0.005
Soil.Source	1	26.30	26.30	1.16	0.290
Soil.Rate	3	292.02	97.34	4.29	0.012
Source.Rate	3	17.37	5.79	0.26	0.857
Soil.Source.Rate	3	69.30	23.10	1.02	0.398
Residual	30	680.49	22.68		
Total	47	1532.71			

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