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Eggshells Improve Soil pH and P Availability in Sandy Loam and Sandy Clay Loamy Soil

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Abstract: The current effective method of mitigating soil acidity is the application of lime. However, the costs associated with acquiring lime make it challenging for small-scale farmers in South Africa. Therefore, the aim of this study was to evaluate the liming potential of ground eggshells relative to aglime and its effect on P availability in two acidic soils differing in textural classes, and its subsequent effect on the growth of Swiss chard (*Beta vulgaris* L.). Two 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. Both lime sources were applied at a rate of 0, 1, 2.5, and 5 t/ha through incubation for 120 days. Our results indicated that applying eggshells and aglime significantly increased soil pH within 7 days ($p < 0.05$) compared to the 0-rate application across all application rates in both soil types. There were no differences ($p > 0.05$) in pH between the two applied lime sources. Plant-available P was not significantly different between the applied lime sources at all application rates and the 0-rate application; however, the two lime sources increased plant-available phosphorus above 25 ppm, which is the minimum health level of plant-available phosphorus. The results of plant yield showed no differences ($p > 0.05$) between the plant dry weights. However, Swiss chard growing at the 0-rate application in the sandy clay loam showed poor and stunted growth while Swiss chard growing at the 0-rate application 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 as a substitute of aglime to increase soil pH. Using eggshells as a substitute for aglime could offer substantial benefits to small-scale farmers by reducing input costs and providing a locally sourced, sustainable alternative. This approach can also enhance economic sustainability in rural communities by promoting the recycling of agricultural by-products and making essential soil amendments more affordable and accessible.

Keywords: acidic; aglime; calcium carbonate; ground eggshell; soil texture

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1. Introduction

Soil acidity is one of the major constraints on agricultural production in South Africa. Approximately 5 million hectares (ha) of South African soil is extremely acidic with an additional 11 million ha being moderately acidic [1]. 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 for most crops. Aluminum (Al) and manganese (Mn) toxicities, certain nutrient deficiencies, and reduced microbial activity and diversity become problematic at lower pH values [2]. Consequently, all these factors can result in reduced crop yield and economic losses for the farmers.

The current method for mitigating soil acidity by large commercial farms in South Africa is applying lime. However, small-scale farmers are unable to afford 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 [2,3]. 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. The alternative liming materials in agriculture include industrial by-products such as fly ash, wood ash, stainless steel slag, and metallurgical slag [4]. The mineralogy and chemical composition of these industrial by-products suggest that they can be used as liming materials [5–7]. However, there are major concerns about using these materials in agriculture since they contain toxic elements, which may contaminate the food chain. On the other hand, rural communities in South Africa consume at least 60 eggs per household per month and these eggshells contain 94 to 97% calcium carbonate ($CaCO_3$) [8,9]. Therefore, eggshells may provide an opportunity to neutralize acidic soils at a lesser price since they form part of domestic waste in rural communities. The advantages of using eggshells as a liming material range from agronomic to environmental. Eggshells contain a high calcium carbonate equivalent (CCE), which ranges from 75% to higher [10]. This suggests that eggshells could effectively neutralize acidic soils to acceptable levels. Additionally, eggshells contain very low levels of potentially toxic elements, such as lead, cadmium, and arsenic. According to a report by [11], arsenic and cadmium were undetectable in the eggshells, while lead averaged just 0.2 ppm. Furthermore, the use of a recyclable and organic resource provides an opportunity to practice sustainable agriculture. However, due to the limited research on the impact of eggshell use for increasing soil pH and soil application, the question remains about the effectiveness of these materials as a liming source.

Daily egg production for commercial use in South Africa has exceeded 30 million and increases annually [12]. These figures reflect only the production from registered producers; therefore, the actual number could be higher, as they do not account for eggs produced by unregistered or smaller-scale producers. One eggshell weighs up to 5.5 g and, therefore, the monthly production of eggs could potentially produce about 4950 tons 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 could potentially produce an additional 5313 tons of eggshell lime. An eggshell's chemical composition is predominantly $CaCO_3$, which is what traditional liming materials are made of, but eggshells would be less expensive since they form part of the domestic waste process.

The aim of the study was to evaluate the liming potential of ground eggshells relative to aglime and their effect on phosphorus availability in two acidic soils differing in textural classes, and their subsequent effect on the Swiss chard yield.

2. Methods and Materials

2.1. Iincubation Trial

2.1.1. Eggshell Collection and Characterization

Eggshells were collected from nearby food outlets (i.e., restaurants, hotels, etc.) and students residing at the North-West University, Mahikeng campus. The eggshells were then cleaned with deionized water, air-dried, ground with a coffee grinder, sieved through a 2 mm mesh, and stored in polyethylene bags under ambient laboratory conditions. Agricultural lime, also known as aglime (dolomitic limestone with 85% CaCO3 and MgCO3), was purchased from NWK in Mahikeng and was also ground and sieved through a 2 mm mesh. Ground eggshells and aglime were analyzed for mineralogy by X-ray diffraction (XRD) using an X-ray diffractometer. Agricultural lime was composed of CaCO3, MgCO3, and quartz (SiO2), whereas the ground eggshells were composed of CaCO3 (Figure 1). The CCE of both aglime and the eggshells were determined using the HCl method [13] and their values were 82.2% and 94.8%, respectively.

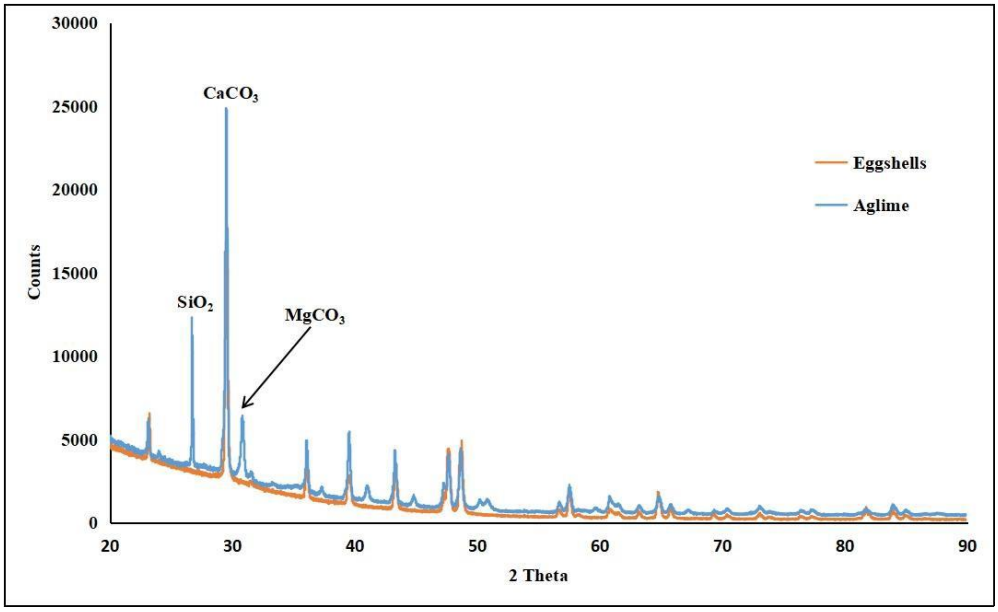

Figure 1. X-ray powder diffraction pattern of ground eggshells (orange) and agricultural lime (blue). The dominant peaks (I/I_i = 100) of the identified minerals are indicated.

2.1.2. 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 2). The sandy clay loam (soil C) was collected at coordinates 26°18′36.0″ S 26°06′36.0″ E at an altitude of 1495 m above sea level. Meanwhile, the sandy loam soil (soil S) was collected at coordinates 26°24′00.0″ S 26°06′36.0″ E, also at an altitude of 1495 m above sea level. The two locations are 14.5 km apart. The parent materials for the sandy clay loam and sandy loam soils were Ventersdorp lava and granite, respectively, with both soils classified as Hutton [14]. The collected soils were air-dried, sieved with a 2 mm mesh and then stored in plastic bags in the greenhouse. Subsamples of the two soils were sent to the South African Sugarcane Research Institute Fertilizer Analytical Services (FAS) for laboratory analysis and the results are presented in Table 1. Further analysis of pH (KCl) and Mehlich 3 extractable P were determined in the university laboratory.

2.1.3. Experiment and Experimental Design

The experiment was a 2 × 2 × 4 factorial experiment in a completely randomized design (CRD), replicated three (3) times. The two soils were weighed up to 4 kg into 2-liter 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 soils were well mixed to promote even distribution of the liming materials within each soil and then equally divided into six small polystyrene foam cups for six sampling days, and to allow for destructive sampling during the duration of the experiment. The soil was watered to field capacity two times a week with deionized water until the completion of the study.

2.1.4. Data Collection

The data collected included exchangeable acidity, plant-available P, and soil pH (KCl). Data were collected on days 7, 14, 30, 60, 90, and 120. Exchangeable acidity was analyzed using the titration method [15]. Plant-available phosphorus was extracted with Mehlich 3 solution and then analyzed using a spectrophotometer at the wavelength of 650 nm [16]. Soil pH was analyzed using a 1 M KCl with a soil-to-solution ratio of 1:2.5 [17].

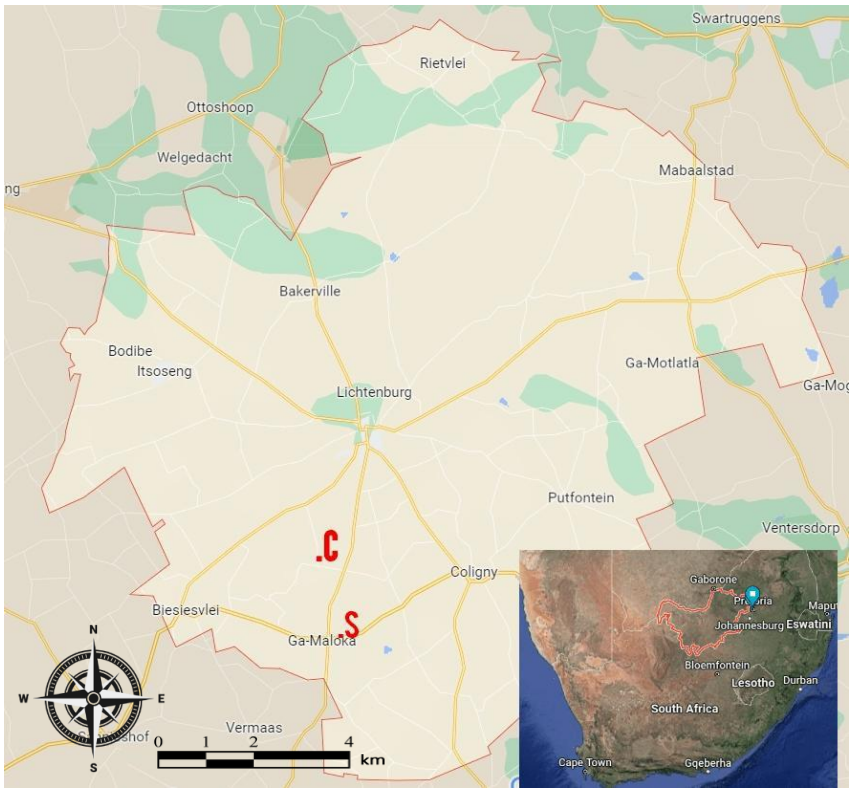

Figure 2. Location of the of the study area. The red letter C (26°18′36.0″ S 26°06′36.0″ E, with an altitude of 1495 m above sea level) indicates the collection location of the sandy clay soil. Meanwhile, the red letter S (26°24′00.0″ S 26°06′36.0″ E, with an altitude of 1495 m above sea level) indicates the collection location of the sandy loam soil.

Table 1. Physical and chemical properties of the two soils used in this study.

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
Field capacity (%)	16.4	12.3

2.2. Pot Trial

2.2.1. Experiment and Experimental Design

The experiment was a 2 × 2 × 4 × 1 factorial experiment with 3 replications arranged in a completely randomized design (CRD). The 2 soils were sandy clay loam and sandy loam, the 2 liming treatments were eggshells and aglime at 4 treatment rates, i.e., 0, 1.0, 2.5, and 5.0 t/ha, and one (1) cultivar of Swiss chard. Six-week-old seedlings of Swiss chard were transplanted to pots containing 8 kg of soil and were watered according to crop requirements using tap water until the completion of the experiment.

2.2.2. Data Collection

Both plant and soil data were collected at the end of the greenhouse experiment. Data collected for the greenhouse experiment encompassed plant yield, and soil pH (KCl) and plant-available phosphorus were measured as described in Section 2.1.4. The leaves of the Swiss chard were washed with deionized water and oven-dried for 24 h at 80 °C and were subsequently weighed and recorded. Plant-available phosphorus and soil pH ware analyzed using the same methods as those used in the incubation trial.

2.3. Statistical Analyses

The collected plant and soil data were subjected to ANOVA using the 18th Edition of Genstat (VSN International, 2009, Hemel Hempstead, UK). The means were separated by Tukey's least significant difference (LSD) at a 5% level of significance. Prior to conducting the ANOVA, the assumptions of data distribution, including homogeneity of variance, were evaluated. Principal component analysis was carried out using jamovi (jamivi version 2.3, 2023).

3. Results

3.1. Incubation Trial

3.1.1. Soil pH

Adding aglime and eggshells significantly ($p < 0.05$) increased the soil pH in both the sandy loam and sandy clay loam soils (Table 2 and Figure 3). The soil pH increased rapidly initially in the first 14 days for both lime sources and the rate of increase was observed to stabilize from day 30 after incubation in all the lime application rates except the control (Figure 3). The rate of increase was significantly higher at all the application rates as compared to the control (Figure 3).

Table 2. ANOVA results of the effect of eggshells and aglime in two soils (sandy clay loam and sandy loamy) on soil pH exchangeable acidity and phosphorus concentration in soil.

		pH		EA		P	
Effects	**Df**	**F**	***p***	**F**	***p***	**F**	***p***
Soil type (S)	1	884.15	<0.001 **	189.41	<0.001 **	28.97	<0.001 **
Lime source (L)	1	7.60	0.006	1.41	0.236	2.75	0.099
Application rate (R)	3	713.05	<0.001 **	358.33	<0.001 **	58.45	<0.001 **
Sampling time (T)	6	334.61	<.0.001 **	118.67	<0.001 **	20.01	<0.001 **
S × L	1	4.80	0.030	0.93	0.337	3.98	0.047
S × R	3	58.74	<0.001 **	19.04	<0.001 **	8.74	<0.001 **
L × R	3	1.97	0.120	3.34	0.020	2.34	0.074
S × T	6	3.00	0.008	42.09	<0.001 **	0.62	0.712
L × T	6	0.87	0.520	0.64	0.695	1.42	0.207
R × T	18	25.46	<0.001 **	8.87	<0.001 **	2.11	0.006
S × L × R	3	1.99	0.117	6.14	<0.001 **	1.33	0.265
S × L × T	6	0.38	0.892	0.86	0.525	1.41	0.212
S × R × T	18	3.34	<0.001 **	1.91	0.016	0.63	0.875
L × R × T	18	0.62	0.883	0.74	0.765	0.98	0.486
S × L × R × T	18	1.11	0.342	0.69	0.820	1.00	0.460

EA = exchangeable acidity, P = phosphorus and ** denote statistical significance at 0.001.

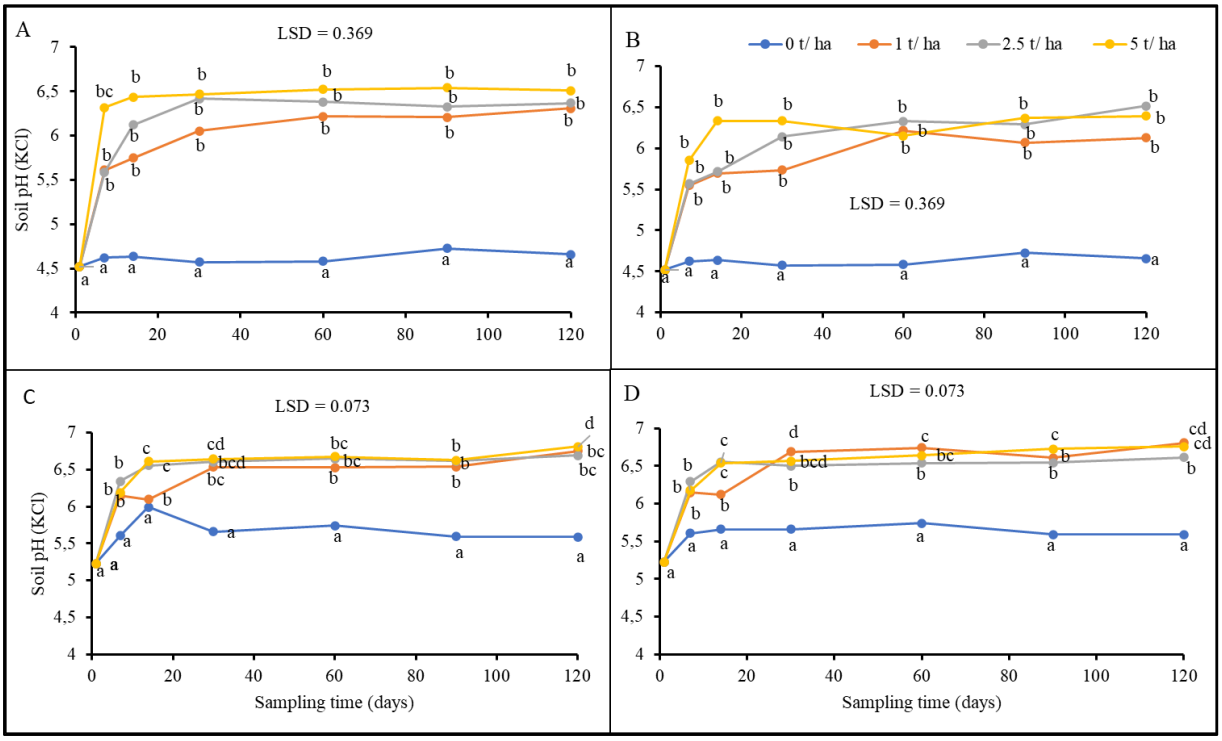

Figure 3. The effect of eggshells (**A**,**C**) and aglime (**B**,**D**) at four application rates (0, 1, 2.5, and 5 t/ha) on the soil pH (KCl) of sandy clay loam (**A**,**B**) and sandy loam (**C**,**D**) over 120 days of the incubation trial. The mean soil pH values were 5.5 for sandy clay loam and 6.1 for sandy loam. Different letters indicate a significant difference across all treatments and all days within each soil type at $p = 0.05$.

Moreover, the results showed no significant difference ($p > 0.05$) between the application rates of 1, 2.5, and 5 t/ha for each source of lime (Figure 4) after 120 days of incubation. However, after 120 days, soil pH under the application of eggshells and aglime in both the soils was significantly ($p < 0.05$) higher than the control at all application rates but there was no significant difference ($p > 0.05$) between the two lime sources at all application rates (Figure 4).

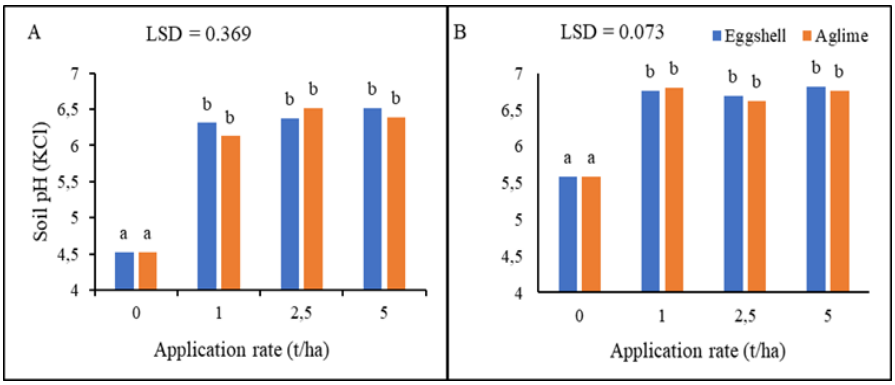

Figure 4. The effect of applied eggshells and aglime at four application rates (0, 1, 2.5, and 5 t/ha) on the soil pH (KCl) of different soil types (**A**) (sandy clay loam) and (**B**) (sandy loam) at day 120 of the incubation trial. The mean soil pH values were 5.9 for sandy clay loam and 6.4 for sandy loam. Different letters indicate a significant difference between all rates within each treatment at $p = 0.05$.

3.1.2. Exchangeable Acidity

The liming treatments significantly ($p < 0.05$) and completely neutralized the acidity of both soils within seven days (Figure 5 and Table 2). 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 was not significantly different ($p < 0.05$) for neutralizing the soil acidity of both soils (Figure 5). Moreover, the applied rates of 1, 2.5, and 5 t/ha of lime were also not significantly different ($p > 0.05$). All the applied rates were similar and, therefore, appeared as one line in the graph, except for the 5 t/ha application of eggshells in clay soil (Figure 5).

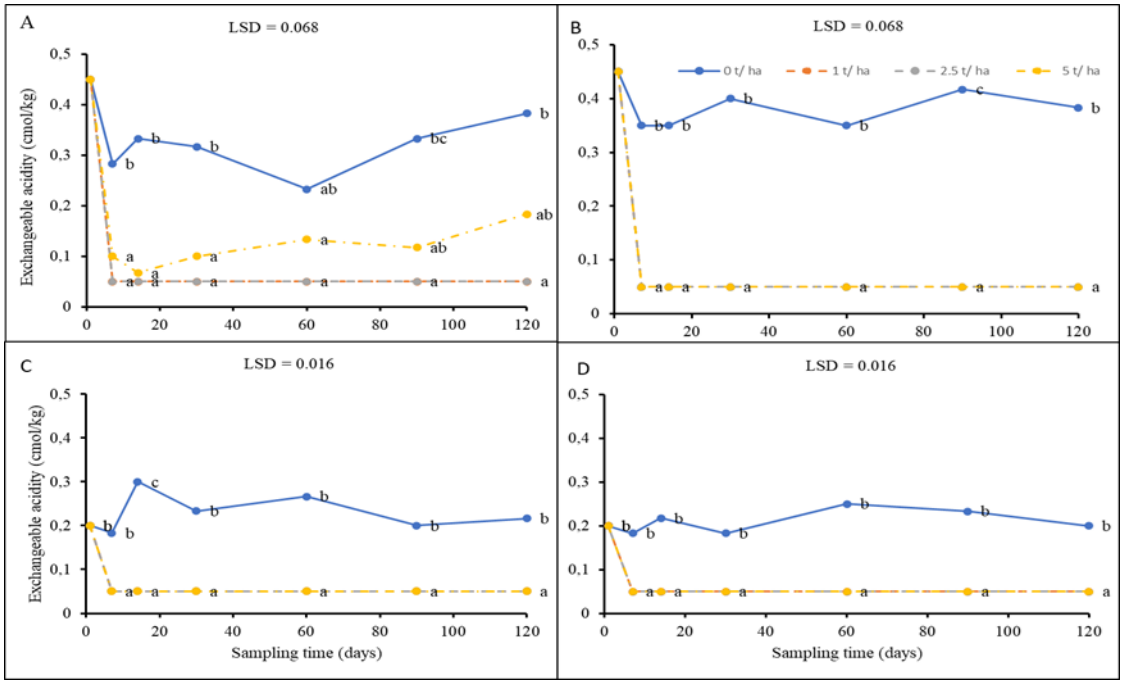

Figure 5. The effect of applied eggshells (**A**,**C**) and aglime (**B**,**D**) at four application rates (0, 1, 2.5, and 5 t/ha) on the exchangeable acidity of sandy clay loam (**A**,**B**) and sandy loam (**C**,**D**) over 120 days of the incubation trial. The mean exchangeable values for sandy clay loam were 0.17 and 0.10 for sandy loam. Different letters indicate a significant difference across all treatments and all days within each soil type at $p = 0.05$.

After 120 days, the exchangeable acidity under the application of eggshells and aglime in both the soils was significantly ($p < 0.05$) lower than the 0-rate application at all application rates, and there was no significant difference ($p > 0.05$) between the two lime sources at all application rates (Figure 6).

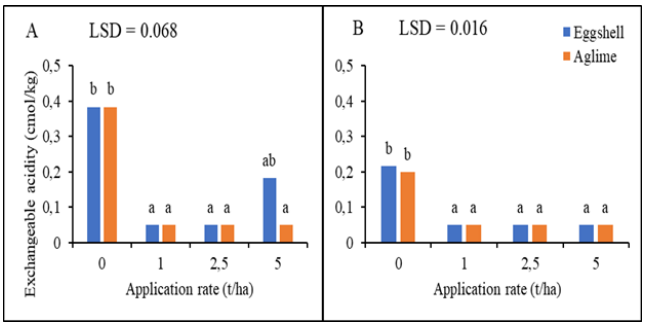

Figure 6. The effect of applied eggshells (blue) and aglime (orange) at four application rates (0, 1, 2.5, and 5 t/ha) on the exchangeable acidity of sandy clay loam (**A**) and sandy loamy (**B**) at day 120 of the incubation trial. The mean exchangeable acidity values were 0.14 for sandy clay loam and 0.09 for sandy loam. Different letters indicate a significant difference between all rates within each soil type at $p = 0.05$.

3.1.3. Plant-Available Phosphorus

The application of eggshells and aglime did not significantly ($p > 0.05$) increase the plant-available phosphorus in comparison to the control (Table 2, $p = 0.099$) for all application rates in sandy clay loam soil, except for 5 t/ha application of aglime treatment at days 60 and 90 (Figure 7). Although this was not significant ($p > 0.05$), a clear trend can be observed that lime had some effect on improving P availability in the soil (Figure 7). Similarly, the application of eggshells 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 eggshells at days 30, 90, and 120 and 5 t/ha application of aglime from day 14 to 120 (Figure 7). 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.

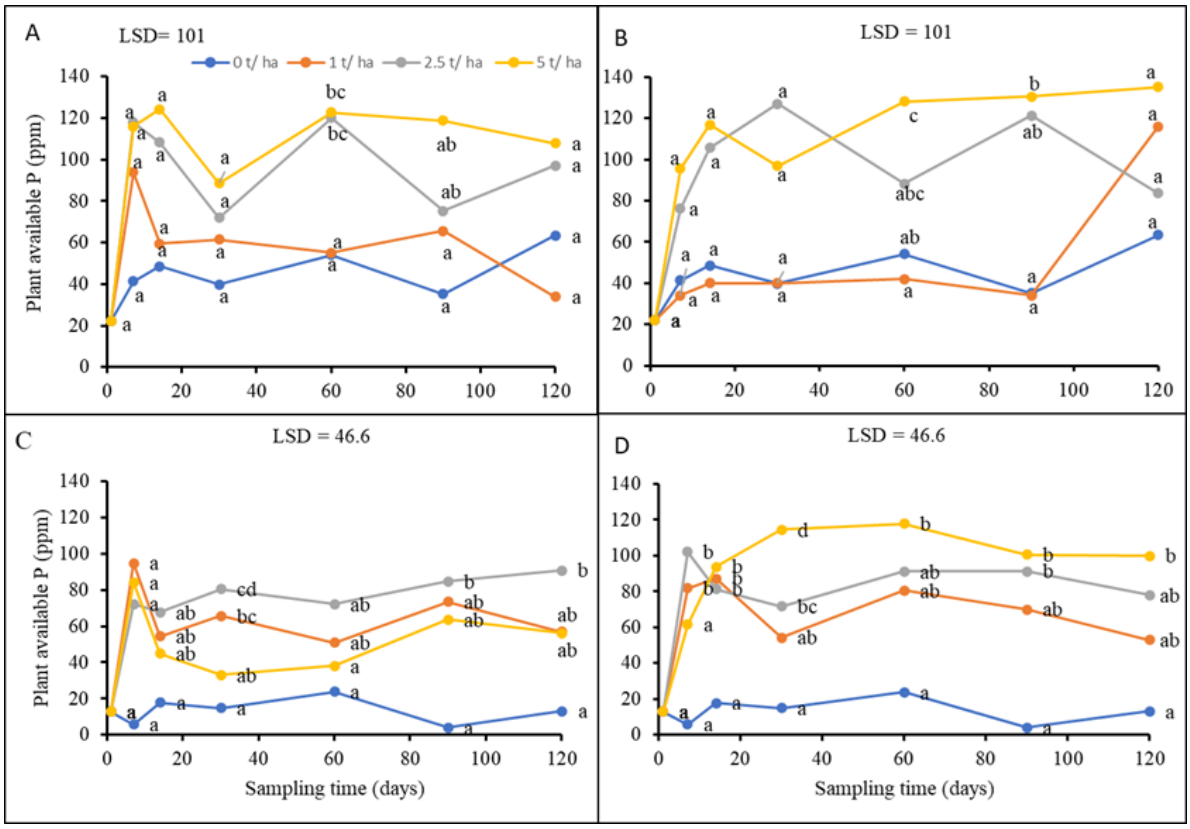

Figure 7. The effect of applied eggshells (**A**,**C**) and aglime (**B**,**D**) at four application rates (0, 1, 2.5, and 5 t/ha) on plant-available phosphorus in a sandy clay loam (**A**,**B**) and sandy loam (**C**,**D**) over 120 days of the incubation trial. Different letters for each soil type and sampling day indicate a significant difference between means across all treatments (source and application rates) and all days within each soil type at $p = 0.05$.

At day 120, there was no significant difference ($p > 0.05$) 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 8).

3.1.4. Multivariate Analysis

The results of the principal component analysis indicated that dimension 1 and dimension 2 contributed 64.9% and 29.5% to the total variation of the soil pH, exchangeable acidity, and available phosphorus under different soil types (Figure 9). Dimension 1 and

dimension 2 of different sources of lime and application and under different sampling dates showed similar percentages. These results clearly indicated that soil pH was inversely related to exchangeable acidity, as was indicated by vectors facing in direct opposite directions. On the other hand, there was some degree of association between soil pH and available P; however, this relationship was not strongly correlated.

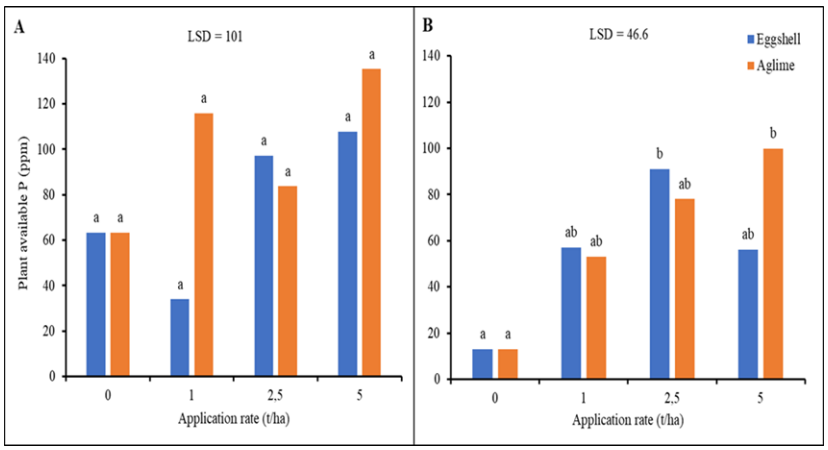

Figure 8. The effect of applied eggshells (blue) and aglime (orange) at four application rates (0, 1, 2.5, and 5 t/ha) on plant-available phosphorus in a sandy clay loam (**A**) and sandy loam (**B**) at day 120 of the incubation trial. The mean plant-available *p* values were 87 for sandy clay loam and 57 for sandy loam. Different letters indicate a significant difference between all rates within each soil type at $p = 0.05$.

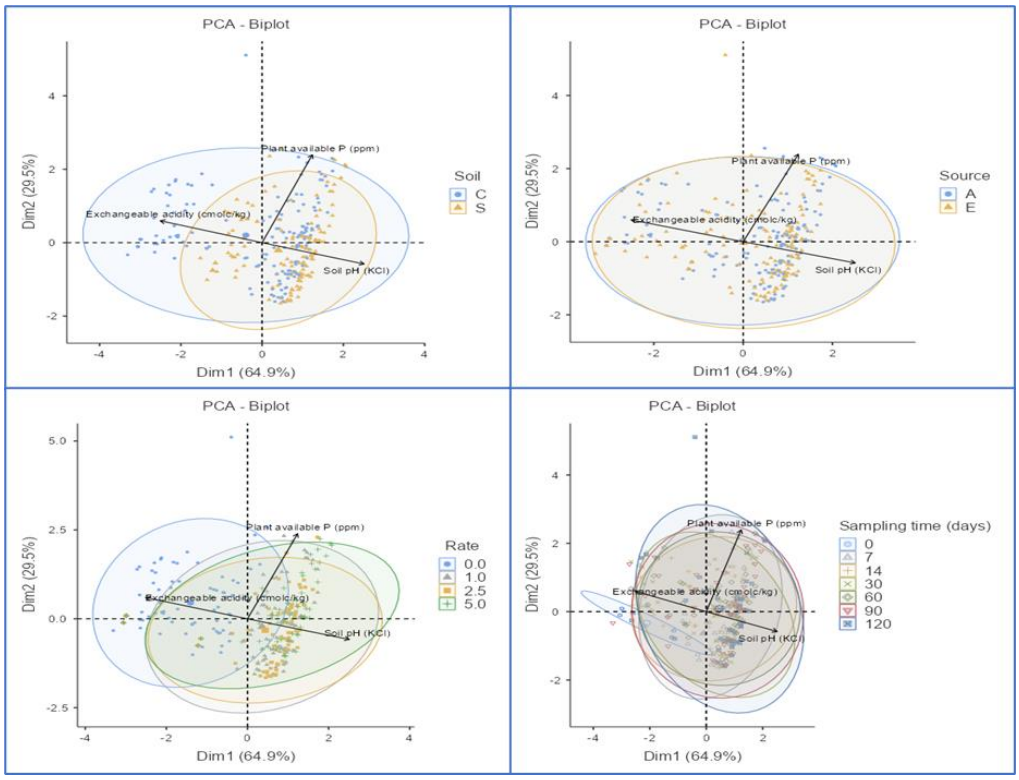

Figure 9. The principal component analysis (PCA) showing the relationship and distribution between the measured variables (pH, exchangeable acidity, and available P) in different soils (C= sandy clay loamy and S= sandy loamy), different lime sources (A= aglime and E= eggshells) and rate (0, 1.0, 2.5, 5.0 t/ha), and different sampling times (0, 7, 14, 30, 60, 90, and 120 days after incubation).

3.2. Pot Trial

3.2.1. Soil pH

The pH of the soils under the application of eggshells and aglime was significantly ($p < 0.05$) higher than their respective 0-rate application at the end of the pot trial (Figure 10). 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 0-rate application. This was unexpected for the 0-rate application, 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 (eggshells and aglime) increased the soil pH significantly more than the 0-rate application, there was no significant difference between the increase in soil pH with the two treatments (aglime and eggshell) at all application rates; moreover, there was no significant difference between the applied rates' (1, 2.5, and 5 t/ha) increase in the soil pH.

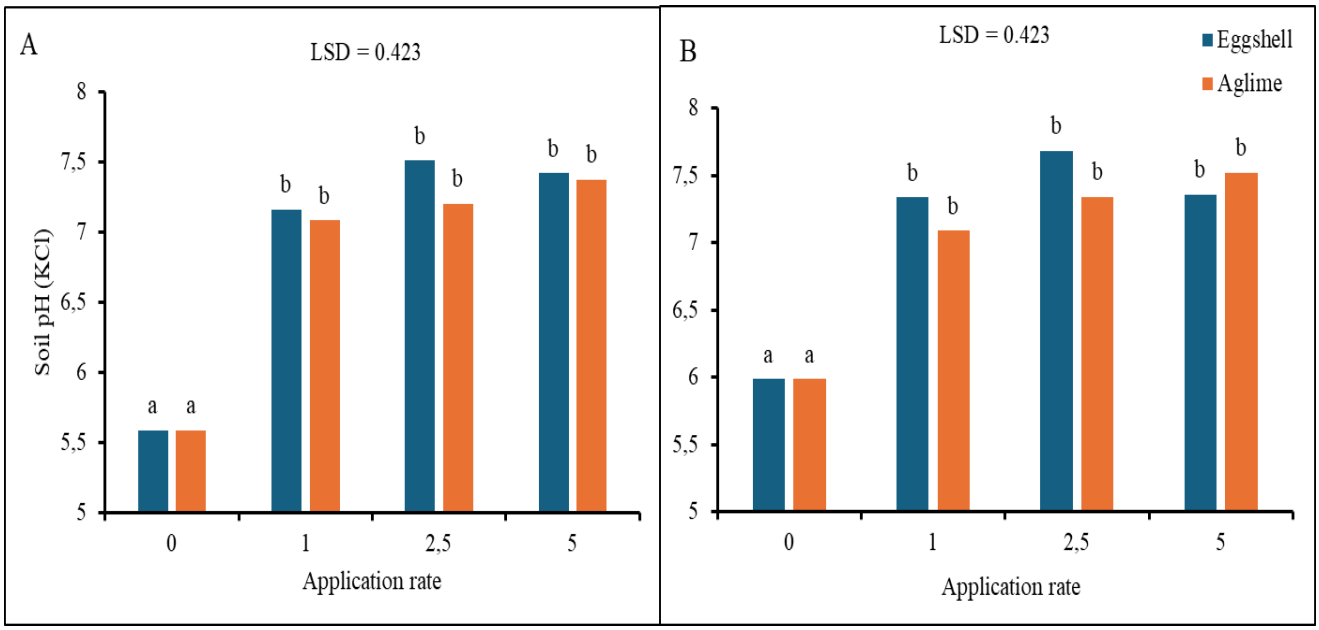

Figure 10. The effect of applied eggshells (blue) and aglime (orange) at four application rates (0, 1, 2.5, and 5 t/ha) on the soil pH (KCl) of sandy clay loam (**A**) and sandy loam (**B**) soil after 120 days of the pot trial. Different letters indicate a significant difference between means for all treatment at $p = 0.05$.

3.2.2. Plant-Available Phosphorus

The application of both eggshells and aglime did not significantly increase ($p > 0.05$) the plant-available phosphorus in comparison to the 0-rate application for all application rates in both soils, except for the 5 t/ha application of eggshells in sandy clay loam (Figure 11). Also, the liming source did not significantly affect the plant-available phosphorus at each application rate in both soils (Figure 11). Additionally, the application rates of both liming materials did not significantly affect the plant-available phosphorus in both soils.

3.2.3. Dry Weight

It was observed that the Swiss chard growing at the 0-rate application in the sandy clay loam soil showed poor and stunted growth throughout the growing season, while the Swiss chard growing at the 0-rate application in the sandy loam soil did not exhibit poor and stunted growth (Figure 12).

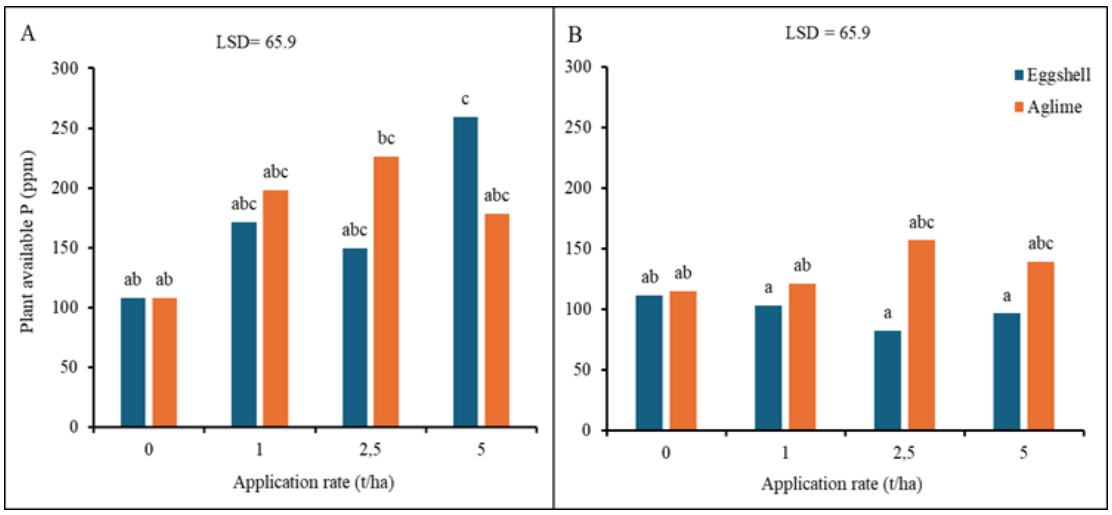

Figure 11. The effect of applied eggshells (blue) and aglime (orange) at four application rates (0, 1, 2.5, and 5 t/ha) on plant-available phosphorus in a sandy clay loam (**A**) and sandy loam soil (**B**) after 120 days of the pot trial. Different letters indicate a significant difference between means for all treatments at $p = 0.05$.

(A) (B)

Figure 12. The 0-rate application plant (**A**) in sandy clay loam soil compared to the eggshell-treated plant (**B**) in sandy clay loam soil after 120 days of the pot trial.

The application of both eggshells and aglime did not significantly increase ($p > 0.05$) the Swiss chard dry weight in comparison to the 0-rate application for all application rates in both soils, except for the 1.0 t/ha application of eggshells in the sandy clay loam (Figure 13). Also, 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.

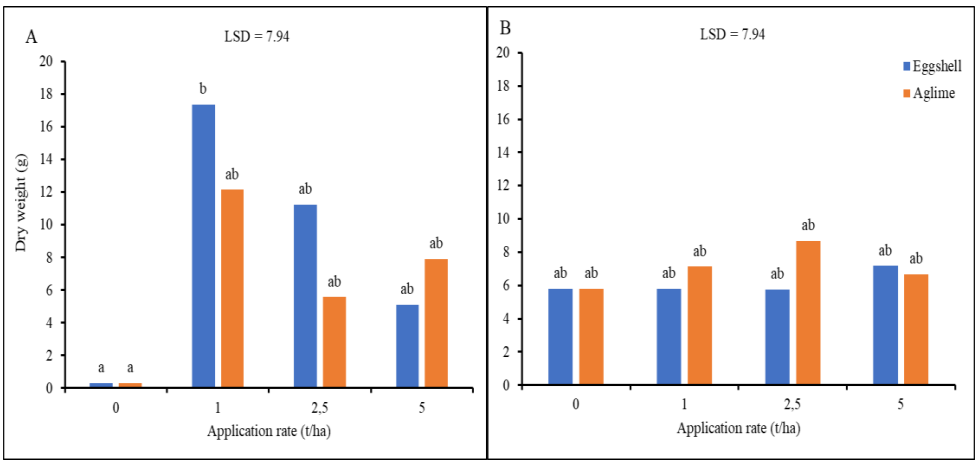

Figure 13. The effect of applied eggshells (blue) and aglime (orange) at four application rates (0, 1, 2.5, and 5 t/ha) on the yield/dry matter of Swiss chard in sandy clay loam (**A**) and sandy loam soil (**B**) after 120 days of the pot trial. Different letters indicate a significant difference at $p = 0.05$.

3.2.4. Multivariate Analysis

The results of the principal component analysis showed that dimension 1 contributed 50.9% and dimension 2 contributed 28.1% to the total variation of soil pH, available P, and dry weight under different soils, different rates of lime, and different sources of lime (Figure 14). The results showed a clear correlation between dry matter accumulation and soil pH. This was apparent in all treatment combinations of soil type, lime application rate, and source (Figure 14). A clear separation between lime application rates (1, 2.5, and 5 t/ha) and the control can also be observed, separated by different circles.

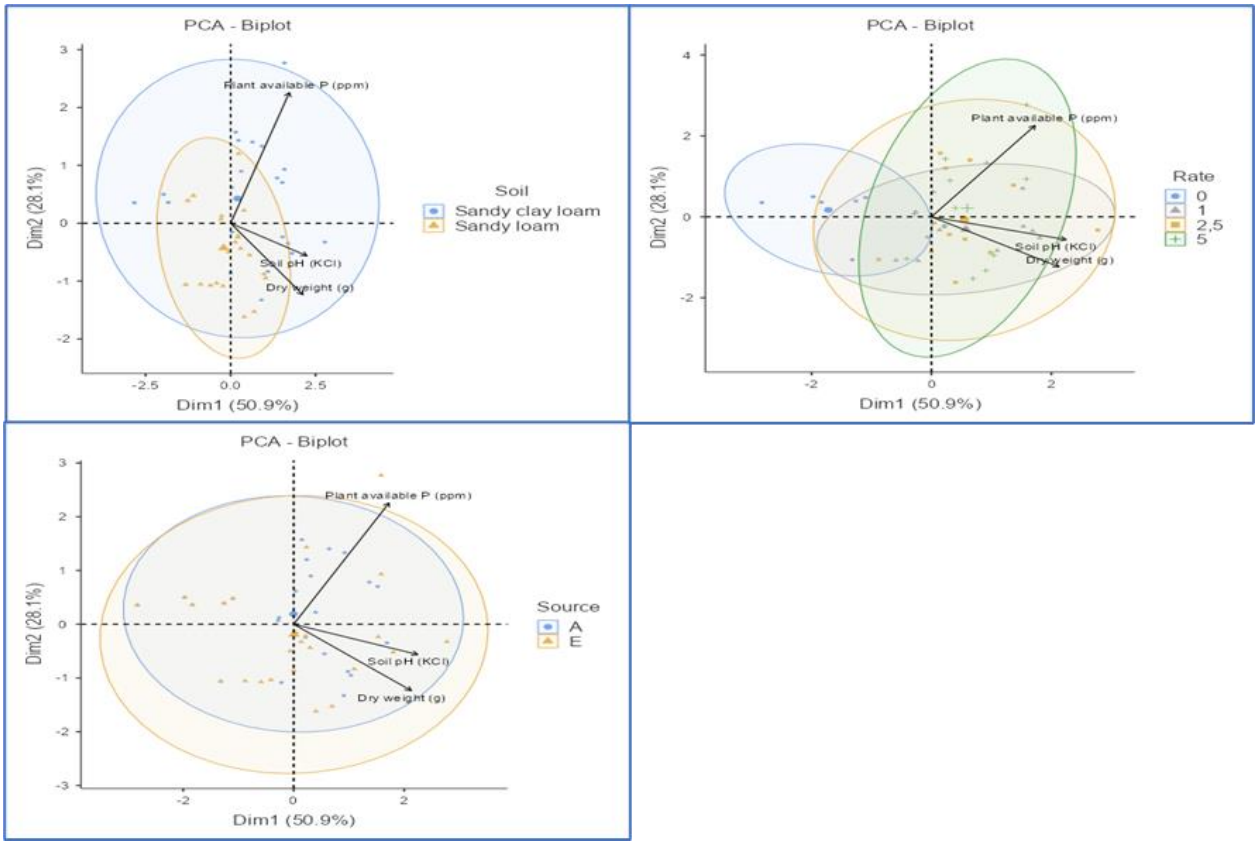

Figure 14. The principal component analysis (PCA) showing the relationship and distribution between the measured variables (pH, available P, and plant dry weight) in different soils with different lime sources (A= aglime and E= eggshells) and rates (0, 1.0, 2.5, 5.0 t/ha).

4. Discussion

The soil pH results in both studies (incubation and pot trial) revealed a significant increase of more than 1.4 units, corresponding to a relative increase of nearly 30%, with the application of ground eggshells or aglime in both soil texture types, but there was no significant difference between the two applied lime sources. Soil pH in the incubation trial increased within seven days of applying the liming materials, aligning with [18], which observed pH changes within two days. This contrasts with other studies where initial pH measurements were taken after two and six months [10,19], potentially missing early pH changes. Our results suggest that soil pH can respond more rapidly than previously documented [19], emphasizing the need for shorter measurement intervals. Future studies should conduct daily pH measurements for at least the first week following liming.

Eggshells and aglime have similar chemical compositions [18]. This was supported by the XRD diffraction patterns of calcite in eggshells and aglime in this study. Since both the liming materials contained similar chemical compositions, 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 a similar calcium carbonate equivalent (CCE) and fineness should have a similar effective neutralizing value (ENV). Earlier studies reported that while eggshells are an effective liming material, they dissolve more slowly compared to aglime [10]. This was later disputed by recent studies that reported a similar dissolution rate of eggshells and aglime [18] and, in some instances, quicker than aglime [18]. However, [18] further emphasized that eggshells are only effective when they are finely ground, although the specific particle size required was not reported.

The soil pH in the pot trial increased at the 0 t/ha rate, which was unexpected since no liming material was applied. This suggests that there was another factor other than the applied liming material which increased the soil pH. The increase in soil pH may have been influenced by the irrigation tap water, which can contain a high concentration of calcium, magnesium, and bicarbonates. These components have the potential to replace hydrogen ions in the soil, thereby raising the soil pH [20]. Moreover, there are reported cases of root-mediated pH changes, which increase the pH in the rhizosphere [21]. 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 have sufficient calcium present to neutralize acidity. The application rates of both liming materials affected the soil pH to a similar extent, as there was no significant difference between them. 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, 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. It has been reported that the dissolution rate of any liming material will stop at a pH of 6.8 [22]. Therefore, the different quantities of lime may similarly increase the soil pH, provided that an equilibrium is reached. However, higher lime application rates may offer the advantage of prolonged soil pH stabilization. This is because excess lime can continuously react with active and exchangeable acidity, maintaining a more stable pH over time.

The soil pH for the incubation trial under the application of the two lime sources quickly increased in the sandy clay loam and plateaued after seven days, whereas in the sandy loam soil, it plateaued after fourteen 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 trial was slightly higher, but not statistically more significant 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. Soil acidity consists of several types, including 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 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 eggshells or aglime significantly neutralized the acidity in the soil in comparison to the 0-rate application 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.

Soil pH affects the nutrients that are soluble in the soil, which subsequently influences the nutrients available to the plant. In acidic soils, nutrients such as phosphorus, calcium, and magnesium become less available to plants, while toxic elements like Al and Mn can become more soluble and toxic [1,2]. This can lead to deficiencies and poor plant growth. It is, therefore, important to regularly test soil pH. Conversely alkaline soils can cause deficiencies in nutrients such as iron, zinc, and manganese as they become less soluble and accessible to the plants. Both extremes can lead to reduced crop yields and lower quality produce. Maintaining a near-neutral pH is ideal for balanced nutrient availability, enhancing plant health and optimizing productivity. Phosphorus is one of the essential nutrients required for plant growth and is considered a macro-nutrient due to its significant roles in various physiological processes. 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 [22]. 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 eggshells and aglime appeared to increase the plant-available phosphorus; however, the increase was not statistically significant compared to the 0-rate application at the 0.5% level. This observed increase may be attributed to the changes in soil pH resulting from the liming treatments. The plant-available phosphorus in the sandy loam at 0 t/ha application rate was below the healthy level of soil phosphorus, which is 25 ppm [22], whereas the 0 t/ha rate in the sandy clay loam was above 25 ppm. Soils with more clay adsorb phosphorus easily [22], since clay particles have a larger surface area and possible higher potential anion adsorption capacity (AEC) for phosphorus adsorption. Increased phosphorus availability in the soil enhances plant health by supporting several physiological processes such as energy transfer through ATP, which improves various cellular functions including photosynthesis and nutrient uptake [22]. This enables the plant to access water and other nutrients more efficiently, leading to improved disease resistance and better stress tolerance.

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 [23]. 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 the 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 the 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 [24]. Although the final soil pH level of the sandy clay loam increased, the increase could have taken a longer time compared to the soils treated with eggshells or aglime, which proved to be quickly reactive from the incubation trial and other related studies.

The application of either eggshells or aglime was not significantly different in increasing the growth of Swiss chard. This is because the applied treatments had similar chemical compositions, which subsequently resulted in similar effects in the soil. Both lime sources significantly increased soil pH to the same extent as compared to the 0-application rates. Consequently, nutrient availability under the application of eggshells and aglime can be expected to be similar per given soil, which would, in turn, influence plant growth similarly. Since the applied rates of both liming materials did not significantly differently increase the soil pH, their influence on the soil and eventually plant growth is likely to be similar. However, this study had several limitations that should be considered when interpreting the results. First, the research was conducted using only two soil types; different soil textures might have interacted differently with eggshells, indicating a need for further investigation across a broader range of soil types. Additionally, the study's duration of 120 days may not have been sufficient to assess the long-term effects of the applied liming materials.

Furthermore, the irrigation water used in the pot trial was not analyzed, which left a gap in understanding how water quality might have interacted with these liming materials.

5. Conclusions

This study demonstrated that both ground eggshells and aglime were effective liming materials and did not increase the soil pH significantly differently. This implies that ground eggshells can be used as an alternative liming source. The recommended application rate for all the liming materials 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, and an economical application rate could 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 their dissolution rate. In the short term, farmers should be encouraged to experiment with eggshells as a liming material due to their potential benefits in neutralizing soil acidity. Policymakers could support this initiative by implementing strategies such as subsidies for the collection and processing of eggshells and establishing educational programs to raise awareness about their effectiveness in soil amendment. By integrating these recommendations with further research, a more sustainable approach to farming could be developed and practiced in South Africa, ultimately contributing to improved soil health and agricultural productivity.

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