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Combined Use of Calciprill and Sodium Silicate Improves Chemical Properties of Low-pH Soil

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Abstract: The highly weathered, acidic tropical soils are generally less fertile because of their low pH, high exchangeable acidity, and Al, Fe, and Mn saturations. Using soil amendments to solve the aforementioned problems is essential. To this end, Calciprill and sodium silicate are worth considering because of their high neutralizing value and dissolution to suppress exchangeable acidity and Al, Fe, and Mn hydrolysis, while at the same time increasing soil pH to improve the availability of inorganic N, available P, exchangeable base cations, and Effective Cation Exchange Capacity (ECEC). An incubation study was conducted to determine the right combination of Calciprill and sodium silicate to reduce exchangeable acidity and Al and Fe hydrolysis to improve inorganic N, available P, exchangeable base cations availability, and ECEC. Bekenu series (*Typic Paleudults*) was incubated with a combined use of Calciprill at 80%, 90%, and 100% Ca saturations and sodium silicate at 90, 105, 120, 135, and 150 kg ha^{-1} for 40, 80, and 120 days, respectively. The laboratory incubation study was carried out using a Completely Randomized Design (CRD) with triplicates to determine the aforementioned treatment effects of the combined use of Calciprill and sodium silicate on soil pH, exchangeable, Al, inorganic N, available P, electrical conductivity, exchangeable cations (K, Ca, Mg, Na, Fe, and Mn), and ECEC using standard procedures. Soils with both amendments significantly increased soil inorganic N, available P, electrical conductivity, exchangeable base cations (K, Ca, Mg, and Na), and ECEC. This was because the amendments increased soil pH by suppressing exchangeable acidity. Moreover, they transformed Al, Fe, and Mn ions into insoluble compounds such as Al and Fe hydroxides and Mn oxides because of their high inherent exchangeable cations, especially Ca and Na. This suggests that the combined use of Calciprill and sodium silicate can enhance soil productivity. The most suitable combination is 7.80 g Calciprill and 9.26 g sodium silicate (C3S5) per one kilogram soil. Additionally, the findings provide fundamental information for future greenhouse and field trials to determine the effects of the suitable combination of the amendments uncovered by this present study on soil health and crop productivity.

Keywords: agronomy; soil fertility rejuvenation; soil acidity mitigation; calcium carbonate; silicon

1. Introduction

In the tropics, high rainfall and warm temperature cause the formation of highly weathered acidic soils because of the leaching of exchangeable base cations (Ca, Mg, K, and

Na) which are replaced by soluble Al^{3+}, Fe^{2+}, Mn^{2+}, and H^+ on the exchange sites of the weathered soils [1,2]. This results in acidification that can impair soil and crop productivity because of the reduced availability of macronutrients (P, K, Ca, and Mg) following the occupation of soluble Al and Fe oxides known to be detrimental to crop health, because these ions are toxic [3]. According to Rahman et al. [4], when soil pH is less than 5.5, exchangeable Al ions are greater than 0.8 $cmol_{(+)} kg^{-1}$, and this significantly reduces soil and crop productivity because of Al toxicity. Moreover, high concentrations of hydrolyzed Al, Fe, and Mn ions can fix P by reacting with HPO_4^{2-} and $H_2PO_4^-$ to form insoluble precipitates. This chemical reaction reduces soil P availability [5]. On the other hand, when soil pH is higher than 7.3, P availability is significantly reduced because of P fixation by Ca^{2+} to form Ca phosphate. Ca phosphate is less soluble in soil solution [6,7]. This explains why the suitable soil pH for desirable soil and crop productivity ranges between 5.5 and 7. Therefore, reducing exchangeable acidity and alleviating Al, Fe, and Mn hydrolysis are essential for maintaining soil pH at a desirable range to improve soil fertility. Aglime such as calcium carbonate ($CaCO_3$) powder and dolomite are commonly used to mitigate soil acidity. Nevertheless, these liming materials are dusty and hazardous during application because carbonates are less soluble in soil water and must be ground to enable the effective neutralization of acid soils. Additionally, their inconsistency and varying effectiveness in neutralizing acid soils are due to their impurities and coarse particles. On the other hand, unbalanced use of dolomite can cause Mg toxicity [8,9]. To reverse these problems, Calciprill and sodium silicate are inorganic liming amendments worth considering as substitutes for $CaCO_3$ powder and dolomite, because Calciprill and sodium silicate are reputed for reducing exchangeable acidity and Al, Fe, and Mn toxicity, in addition to providing base cations such as Ca and Mg.

Calciprill is a 2 to 6 mm prill made from very fine high-purity limestone which contains approximately 95% calcium carbonate ($CaCO_3$). Thus, it is an excellent source of Ca which is an essential nutrient for building plant cell structures. Moreover, the neutralizing value of Calciprill is 99. With its large particle size of 2 to 6 mm, it has an advantage over aglime because of reduced product losses through dust drift. The prill is formulated to breakdown readily on contact with soil water; thus, it is highly reactive to a rapid increase in pH, followed by a fast response from crops. Furthermore, because of its high purity, the required amount of Calciprill needed to mitigate soil acidity is only 10% to 20% of the quantity of aglime, suggesting a reduced cost of production in cropping systems [10]. Sodium silicate (Na_2SiO_3) is a 100% water-soluble white granular silicon fertilizer with a high effective silicon content (soluble silica content of 50% to 60%). Due to its higher solubility compared with slag silicon fertilizer, its absorption rate is higher than that of slag silicon fertilizer which is insoluble in soil. Thus, the amount of sodium silicate used in this present study was only 10% to 20% of that of slag silicon fertilizer. It is a silicon fertilizer that is used to enhance crop resistance towards pests and diseases, cell wall thickness, crop lodging incidence, promote root growth, and prevent root rot [11–13]. Additionally, sodium silicate can increase soil stability to reduce nutrient leaching and runoff [14,15].

There is a dearth of information on the combined use of Calciprill and sodium silicate to fix exchangeable acidity and Al, Fe, and Mn hydrolysis to improve soil fertility. The question of the right combination of Calciprill and sodium silicate to reduce the exchangeable acidity and Al, Fe, and Mn hydrolysis to improve inorganic N, available P, electrical conductivity, exchangeable cations (K, Ca, Mg, and Na), and ECEC has not been answered. Answering this research question is essential because both amendments are alkaline materials that are capable of increasing soil pH rapidly because of their higher purity and solubility compared with other existing liming materials. The rapid increase in soil pH to an optimum range in a shorter time can reduce soil exchangeable acidity, Al, Fe, and Mn via neutralization of exchangeable H^+ and transformation of soluble Al, Fe, and Mn ions into insoluble precipitates. This does not only improve soil fertility because of increased nutrient availability at optimum soil pH, but it also stabilizes soil structure to optimize nutrient use efficiency in crop production. Therefore, it is hypothesized that the combined

use of Calciprill and sodium silicate can improve soil chemical properties by providing sufficient Ca and Na ions to increase soil pH through neutralization of exchangeable H^+ and transformation of soluble Al, Fe, and Mn ions into insoluble precipitates. Thus, the objective of this incubation study was to determine the right combination of Calciprill and sodium silicate to reduce exchangeable acidity and Al, Fe, and Mn hydrolysis to improve inorganic N, available P, electrical conductivity, exchangeable cations, and ECEC.

2. Materials and Methods

2.1. Soil Sampling and Amendment Preparation

The soil used in this study was Bekenu series (*Typic Paleudults*) because it is a tropical acid soil that is commonly cultivated with different crops [16]. According to Paramananthan [16], Bekenu series is classified as a fine loamy soil made up of silica (siliceous in nature) with an isohyperthermic soil temperature regime, because the average temperature is 22 °C and above over the entire year at 50 cm depth from soil surface and the temperature change is less than 5 °C in different seasons. The parent material of the red-yellow sedimentary rocks suggests the presence of ferric iron (Fe^{3+}) in this soil [17]. Moreover, *Typic Paleudults* have a deep and well-drained profile; thus, they are prone to base cation leaching because of high rainfall. The soil sample was collected in an area that has not been cultivated at Universiti Putra Malaysia Bintulu Campus, Sarawak, Malaysia with the geographical coordinates of latitude 03°20′ N and longitude 113°07′ E. The soil was collected in a pedon with specifications of 1 m length × 1 m width × 0.2 m depth using shovel and hoe. Thereafter, the soil was air dried, manually crushed, and sieved to pass a 2 mm sieve. The sieved soil was bulked for homogenizing before setting up the incubation study. The Calciprill and sodium silicate used in this incubation study were supplied by Humibox Sdn. Bhd., Kuala Lumpur, Malaysia and Omya Asia Pacific Sdn. Bhd., Kuala Lumpur, Malaysia. The procedures used to characterize these amendments were similar to those for the soil.

2.2. Initial Characterization of Soil, Calciprill, and Sodium Silicate

Soil pH and electrical conductivity were determined by mixing air-dried soil with 1 M KCl and distilled water in a ratio of 1:2.5, respectively, followed by shaking at 180 rpm for 15 min using an orbital shaker [18]. The soil pH_{KCl} was determined using a digital pH meter (SevenEasy pH, Mettler-Toledo GmbH, Greifensee, Switzerland) after shaking, whereas the soil samples in distilled water were left overnight for equilibration before determining pH. Electrical conductivity was determined using EC meter (SevenEasy Conductivity, Mettler-Toledo GmbH, Switzerland). Soil bulk density was determined using the core ring method [19]. Soil texture was determined using the hydrometer method [20]. Soil total organic matter (TOM) and total organic carbon (TOC) were determined using the loss on ignition method [21]. Soil exchangeable acidity, Al^{3+}, and H^+ were determined using the acid–base titration method [22].

Total N was determined using the Kjeldahl method [19], followed by steam distillation and colorimetric titration [23]. Soil total P was extracted as described by Tan [19] and Taylor [24] was used for the blue color development [25]. Total cations (K^+, Ca^{2+}, Mg^{2+}, Na^+, Fe^{2+}, and Mn^{2+}) were determined using the aqua regia method [19]. Soil exchangeable NH_4^+ and available NO_3^- were determined using the method described by Keeney and Nelson [26]. Soil available P and exchangeable cations (K^+, Ca^{2+}, Mg^{2+}, Na^+, Fe^{2+}, and Mn^{2+}) were extracted using Mehlich's No.1 double acid solution (a mixture of 0.05 M HCl and 0.025 M H_2SO_4) in a ratio of 1:4 (soil double acid) [27]. Available P determination was performer using Ultraviolet-Visible Spectrophotometry (Lambda 25, Perkin Elmer) after the molybdenum blue colorimetric method [25]. Exchangeable cations were determined using Atomic Absorbance Spectrophotometry (AAnalyst 800, Perkin Elmer, CT). Effective Cation Exchange Capacity was determined by summing the charge equivalent of exchangeable K, Ca, Mg, Na, Mn, Fe, Al, and H [28]. For the soil samples whose pH were less than 6.5, exchangeable H was included in the calculation; for the soil samples whose pH were higher

than 6.5, exchangeable H was not included in the calculations. The ECEC was calculated using the following formulae:

$$ECEC_{(pHKCl<6.5)} \ (cmol_{(+)} \ kg^{-1}) = \sum(\text{exchangeable K + Ca + Mg + Na + Mn + Fe + Al + H}) \tag{1}$$

$$ECEC_{(pHKCl>6.5)} \ (cmol_{(+)} \ kg^{-1}) = \sum(\text{exchangeable K + Ca + Mg + Na + Mn + Fe + Al}) \tag{2}$$

2.3. Soil Incubation Study

A soil incubation experiment was conducted in the Soil Science Laboratory at the Department of Crop Science, Universiti Putra Malaysia Bintulu Campus, Sarawak, Malaysia. From the bulked soil, 1 kg of the air-dried soil was weighed using an electronic weighing balance for each replicate and kept in a plastic container with a size of 15 cm in diameter and 12 cm in height. After the initial characterization, the application rates of Calciprill and sodium silicate were fixed in accordance with the targeted soil calcium saturation [29,30] and average Si uptake and planting density of black pepper (*Piper nigrum*) [31,32], respectively. Black pepper is the test crop for our upcoming greenhouse and field trials. The application rates of Calciprill were fixed at Ca saturation of 80%, 90%, and 100%, after which they were converted to per one kilogram of soil at 6.22 g (C1), 7.01 g (C2), and 7.80 g (C3), respectively. The application rates of sodium silicate were fixed at the recommended rates of 90 kg ha^{-1}, 105 kg ha^{-1}, 120 kg ha^{-1}, 135 kg ha^{-1}, and 150 kg ha^{-1}, after which they were converted to per one kilogram soil basis at 5.55 g (S1), 6.48 g (S2), 7.41 g (S3), 8.33 g (S4), and 9.26 g (S5), respectively. Thereafter, the Calciprill, sodium silicate, and soil were mixed thoroughly. There was an additional treatment of soil only (C0S0). Therefore, there were 16 treatments for each batch of incubation arranged in a Completely Randomized Design (CRD) with three replicates per treatment. Details of the treatments evaluated are summarized in Table 1.

Table 1. Details on combined use of Calciprill and sodium silicate in the soil incubation study.

Treatment	Soil (kg)	Calciprill (g)	Sodium Silicate (g)
C0S0	1.0	-	-
C1S1	1.0	6.22	5.55
C1S2	1.0	6.22	6.48
C1S3	1.0	6.22	7.41
C1S4	1.0	6.22	8.33
C1S5	1.0	6.22	9.26
C2S1	1.0	7.01	5.55
C2S2	1.0	7.01	6.48
C2S3	1.0	7.01	7.41
C2S4	1.0	7.01	8.33
C2S5	1.0	7.01	9.26
C3S1	1.0	7.80	5.55
C3S2	1.0	7.80	6.48
C3S3	1.0	7.80	7.41
C3S4	1.0	7.80	8.33
C3S5	1.0	7.80	9.26

After mixing the soil with Calciprill and sodium silicate, the mixed soil samples were moistened with distilled water up to 40% to 60% of the soil water holding capacity and this represented the field capacity of the soil used in this present study. The mixed soil samples were covered with the lid of the container to prevent excessive moisture loss. Each lid had four perforations to enable good aeration. The soil samples were incubated for 40 days, 80 days, and 120 days, respectively. When needed, each soil sample was carefully sprayed with 5 mL of distilled water to maintain sufficient soil moisture for consistent chemical reactions between soil and amendments. At the end of the incubation study, the soil samples were air dried and manually crushed using mortar and pestle. The crushed soil samples were sieved to pass a 2 mm sieve for chemical analyses. The soil chemical

analyses included soil pH_{KCl}, electrical conductivity, exchangeable NH_4^+, available NO_3^-, available P, exchangeable cations (K^+, Ca^{2+}, Mg^{2+}, Na^+, Fe^{2+}, Mn^{2+}, and Al^{3+}), and ECEC using the procedures as described previously.

2.4. Statistical Analysis

The data collected were analyzed using a linear mixed effects model (Proc MIXED) to detect the significance of treatments, with treatment as the fixed effect and days of incubation as a random effect. Data subjected to the linear mixed effects model test were not significant for the random effect; thus, Multivariate Analysis of Variance (MANOVA) was performed using Proc GLM, followed by Tukey's HSD test for mean comparison at $p \leq 0.05$ to determine if there were any significant differences among the treatments. The statistical software used was Statistical Analysis System 9.4.

3. Results and Discussions

3.1. Initial Physio-Chemical Properties of Soil, Calciprill, and Sodium Silicate

The selected physio-chemical properties of the soil are summarized in Table 2. It was a loamy soil (sand, silt, and clay were 48.2%, 24.2%, and 27.6%, respectively) with a bulk density of 1.20 g cm^{-3}. The parent material of the red-yellow sedimentary rocks explains why Bekenu series is high in total Fe (5960.7 ppm) but lower in total cation saturation, including total K (175.0 ppm), Ca (420.0 ppm), Mg (103.3 ppm), and Na (623.3 ppm), resulting in the formation of a typical acidic soil with a pH_{water} of 5.127 and a pH_{KCl} of 3.94. Because the pH of this soil was less than 5.5, it was high in exchangeable acidity (1.21 cmol$_{(+)}$ kg^{-1}), Al^{3+} (1.03 cmol$_{(+)}$ kg^{-1}), and H^+ (0.18 cmol$_{(+)}$ kg^{-1}) but notably, exchangeable Al^{3+} of this soil exceeded the threshold of 0.8 cmol$_{(+)}$ kg^{-1}. This suggests that the soil was saturated with Al toxicity and this explains its low available P (1.24 ppm) because of Al fixation; thus, it required the application of Calciprill and sodium silicate to increase its pH to a desirable range of 5.5 to 7 [19]. Furthermore, it was a mineral soil, with its organic matter content of 7.24% and organic carbon content of 4.2%, because a typical mineral soil does not contain over 20% organic carbon without prolonged water saturation [16]. The deep and well-drained profile of Bekenu series suggests the low exchangeable base cations saturation of this soil. The decreasing order of exchangeable cations is: K^+ (76.0 ppm), Mg^{2+} (20.4 ppm), Ca^{2+} (17.1 ppm), and Na^+ (7.84 ppm). The soil had the highest exchangeable Fe^{2+} concentration (476.9 ppm) compared with other exchangeable cations because of its parent material. This high Fe^{2+} can also fix P.

The selected chemical properties of the Calciprill and sodium silicate are summarized in Table 3. Both Calciprill and sodium silicate are base amendments that can be used to increase the pH of Bekenu series (*Typic Paleudults*). This is because the pH_{water} and pH_{KCl} of Calciprill were 7.77 and 7.78, respectively, whereas those of the sodium silicate were 12.96 and 12.92, respectively. The EC of sodium silicate was higher (113.17 dS m^{-1}) compared with that of the Calciprill (3.11 dS m^{-1}). Both Calciprill and sodium silicate had low exchangeable NH_4^+ and available NO_3^-, suggesting that additional N fertilizers will be needed to meet crop N requirements. The sodium silicate can be used to increase soil available P because of its higher P availability (10.90 ppm) compared with the soil (1.24 ppm) and Calciprill (1.18 ppm). Based on the base exchangeable cations, the Calciprill is a liming material that is made up of highly purified $CaCO_3$ with a determined exchangeable Ca^{2+} of 9696.81 ppm, followed by exchangeable Na^+, K^+, and Mg^{2+} of 1903.65 ppm, 311.69 ppm, and 104.23 ppm, respectively. Additionally, the sodium silicate is a base amendment that is mainly formed by Na_2O and SiO_2, with exchangeable Na^+ and Si concentrations of 100,749.90 ppm and 71.33%, respectively (Table 3). According to Ma and Takahashi [33] and Schaller et al. [34], the Si in sodium silicate does not only increase soil pH, but it also improves soil P availability because Si has a high affinity for Fe ions. The reaction unlocks fixed P and C.

Table 2. Selected physio-chemical properties of Bekenu series (*Typic Paleudult*).

Soil Properties	Value Determined (Mean $\pm$ S.E. [1])
Soil bulk density (g cm^{-3})	1.20 ± 0.07
Soil texture	Sand: 48.2%; Silt: 24.2%; Clay: 27.6% $\therefore$ Loam soil
pH$_{water}$	5.127 ± 0.003
pH$_{KCl}$	3.94 ± 0.01
Electrical conductivity (dS m^{-1})	0.009 ± 0.01
Total organic matter (%)	7.24 ± 0.69
Total organic carbon (%)	4.2 ± 0.4
Total N (%)	0.15 ± 0.01
————————————(ppm)————————————	
Total P	6.50 ± 0.14
Total K	175.0 ± 11.5
Total Ca	420.0 ± 34.0
Total Mg	103.3 ± 15.9
Total Na	623.3 ± 24.2
Total Fe	5960.7 ± 309.9
Total Mn	16.8 ± 0.8
Exchangeable NH$_4^+$	28.02 ± 0.00
Available NO$_3^-$	15.88 ± 0.93
Available P	1.24 ± 0.08
Exchangeable K$^+$	76.0 ± 21.2
Exchangeable Ca^{2+}	17.1 ± 4.7
Exchangeable Mg^{2+}	20.4 ± 0.8
Exchangeable Na$^+$	7.84 ± 0.40
Exchangeable Fe^{2+}	476.9 ± 24.8
Exchangeable Mn^{2+}	6.1 ± 0.2
————————————(cmol$_{(+)}$ kg^{-1})————————————	
Exchangeable acidity	1.21 ± 0.01
Exchangeable Al^{3+}	1.03 ± 0.01
Exchangeable H$^+$	0.18 ± 0.01
Cation Exchange Capacity	7.70 ± 0.06

[1] S.E. = Standard error.

Table 3. Selected chemical properties of Calciprill and sodium silicate.

Chemical Properties	Calciprill (Mean $\pm$ S.E.)	Sodium Silicate (Mean $\pm$ S.E.)
pH$_{water}$	7.77 ± 0.02	12.96 ± 0.03
pH$_{KCl}$	7.78 ± 0.06	12.92 ± 0.03
EC [1] (dS m^{-1})	3.11 ± 0.12	113.17 ± 1.45
————————————(ppm)————————————		
Exchangeable NH$_4^+$	7.47 ± 0.93	8.41 ± 0.00
Available NO$_3^-$	8.41 ± 0.00	12.14 ± 0.93
Available P	1.18 ± 0.06	10.90 ± 0.69
Exchangeable K$^+$	311.69 ± 11.31	260.28 ± 2.74
Exchangeable Ca^{2+}	9696.81 ± 100.20	1.41 ± 0.01
Exchangeable Mg^{2+}	104.23 ± 1.53	1.87 ± 0.06
Exchangeable Na$^+$	1903.65 ± 38.48	$100,749.90 \pm 2027.58$
Exchangeable Fe^{2+}	49.23 ± 3.83	30.26 ± 1.08
Exchangeable Mn^{2+}	6.61 ± 0.08	17.85 ± 0.45
Total Si (%)	n.d. [2]	71.33 ± 0.08

[1] EC = Electrical conductivity; [2] n.d. = not determined.

3.2. Combined Use of Calciprill and Sodium Silicate on Soil pH_{KCl}, Exchangeable Aluminium, Iron, and Manganese Ions

Soil pH_{KCl} for the combined use of Calciprill and sodium silicate treatments significantly increased to the range of 7.69 to 8.21 at 40 DAI, 7.71 to 8 at 80 DAI, and 7.71 to 8.19 at 120 DAI compared with soil only (C0S0) at 40 DAI (3.73), 80 DAI (3.63), and 120 DAI (3.71) (Table 4). The increase in soil pH_{KCl} was due to the significant reduction in the soil exchangeable H^+ compared with soil only (C0S0) because soil pH is inversely proportional to the concentration of soil exchangeable H^+. Additionally, this was due to the neutralization of H^+ by carbonate ions (CO_3^{2-}) released by the Calciprill into the soil solution. This resulted in the significant reduction in exchangeable acidity and H^+. One mole of CO_3^{2-} ion reacts with two moles of H^+ ions to produce carbonic acid (H_2CO_3) as an intermediate, followed by breaking down into water and carbon dioxide [17]. The release of base cations such as K^+, Ca^{2+}, Mg^{2+}, and Na^+ from the amendments also contributed to the increase in the soil pH and immobilization of H^+. This finding is comparable to that of Cai et al. [35] who reported that the addition of amendments with a higher base saturation to acidic soils increases their base saturation; thus, improving the immobilization of H^+ via exchange reactions between soils and amendments. The H^+ ions released during nitrification and base cation uptake by plants via ion exchange reaction can be neutralized by $CaCO_3$ through continued dissolution over time; thus, resulting in increased soil pH buffering capacity [36].

Table 4. Mean soil pH_{KCl} in relation to combined use of Calciprill and sodium silicate at forty, eighty, and one hundred and twenty days incubation.

Treatments	Soil pH_{KCl}		
	40 Days	**80 Days**	**120 Days**
C0S0	3.73 g $\pm$ 0.01	3.63 g' $\pm$ 0.00	3.71 f'' $\pm$ 0.02
C1S1	7.69 f $\pm$ 0.03	7.71 f' $\pm$ 0.04	7.71 e'' $\pm$ 0.05
C1S2	7.83 ef $\pm$ 0.03	7.78 def' $\pm$ 0.05	7.97 de'' $\pm$ 0.04
C1S3	7.90 de $\pm$ 0.04	7.88 abcde' $\pm$ 0.03	8.04 abc'' $\pm$ 0.07
C1S4	8.03 bcd $\pm$ 0.01	7.97 ab' $\pm$ 0.01	8.07 abc'' $\pm$ 0.05
C1S5	8.14 ab $\pm$ 0.04	8.00 a' $\pm$ 0.01	8.05 abc'' $\pm$ 0.01
C2S1	7.89 de $\pm$ 0.02	7.74 ef' $\pm$ 0.02	7.77 de'' $\pm$ 0.02
C2S2	7.94 cde $\pm$ 0.01	7.83 bcdef' $\pm$ 0.02	7.97 bcd'' $\pm$ 0.03
C2S3	8.00 bcde $\pm$ 0.04	7.92 abcd' $\pm$ 0.03	7.97 bcd'' $\pm$ 0.04
C2S4	7.98 bcde $\pm$ 0.08	7.92 abcd' $\pm$ 0.02	8.06 abc'' $\pm$ 0.03
C2S5	8.21 a $\pm$ 0.02	8.02 a' $\pm$ 0.03	8.11 ab'' $\pm$ 0.02
C3S1	7.93 cde $\pm$ 0.02	7.82 cdef' $\pm$ 0.03	7.88 cde'' $\pm$ 0.03
C3S2	8.00 bcde $\pm$ 0.03	7.79 def' $\pm$ 0.03	7.95 bcd'' $\pm$ 0.07
C3S3	8.08 abc $\pm$ 0.01	7.92 abcd' $\pm$ 0.04	8.06 abc'' $\pm$ 0.02
C3S4	8.12 ab $\pm$ 0.04	7.97 abc' $\pm$ 0.01	8.08 abc'' $\pm$ 0.03
C3S5	8.15 ab $\pm$ 0.03	7.99 a' $\pm$ 0.03	8.19 a'' $\pm$ 0.04

Means (value $\pm$ standard error) with different letters within the same column indicate significant differences using Tukey's test with $p \leq 0.05$. Small letters, small letters with ', and small letters with '' indicate mean comparison at forty, eighty, and one hundred and twenty days incubation, respectively.

Notably, the combined use of Calciprill and sodium silicate significantly reduced exchangeable Al compared with soil only (C0S0) without these amendments. At 40 DAI, 80 DAI, and 120 DAI, the exchangeable Al for the soils with the amendments ranged from 0.03 to 0.04 $cmol_{(+)}$ kg^{-1}, 0.02 to 0.04 $cmol_{(+)}$ kg^{-1}, and 0.03 to 0.04 $cmol_{(+)}$ kg^{-1}, respectively. These values are below the threshold of Al toxicity at 0.8 $cmol_{(+)}$ kg^{-1} and those for soil only (C0S0) at 40 DAI (1.05 $cmol_{(+)}$ kg^{-1}), 80 DAI (0.99 $cmol_{(+)}$ kg^{-1}), and 120 DAI (1.06 $cmol_{(+)}$ kg^{-1}) (Table 5). These results suggest that the exchangeable Al ions had been greatly suppressed because the exchangeable Al was precipitated as insoluble Al hydroxides [5]. Al hydrolysis to produce H ions decreases with increasing pH [17,37]. For example, a complete hydrolysis of one mole of Al^{3+} produces three moles of H^+ to decrease

soil pH. In the present study, this reaction was impeded because of the acid neutralizing ability of the Calciprill and sodium silicate.

Table 5. Mean soil exchangeable aluminum in relation to combined use of Calciprill and sodium silicate at forty, eighty, and one hundred and twenty days incubation.

Treatments	Soil Exchangeable Al^{3+} ($cmol_{(+)}$ kg^{-1})		
	40 Days	80 Days	120 Days
C0S0	1.05 a $\pm$ 0.006	0.99 a' $\pm$ 0.060	1.06 a'' $\pm$ 0.023
C1S1	0.03 b $\pm$ 0.03	0.03 b' $\pm$ 0.003	0.04 b'' $\pm$ 0.003
C1S2	0.03 b $\pm$ 0.03	0.02 b' $\pm$ 0.000	0.04 b'' $\pm$ 0.003
C1S3	0.03 b $\pm$ 0.03	0.02 b' $\pm$ 0.000	0.04 b'' $\pm$ 0.003
C1S4	0.03 b $\pm$ 0.000	0.02 b' $\pm$ 0.003	0.04 b'' $\pm$ 0.006
C1S5	0.03 b $\pm$ 0.000	0.03 b' $\pm$ 0.003	0.04 b'' $\pm$ 0.000
C2S1	0.03 b $\pm$ 0.000	0.04 b' $\pm$ 0.003	0.03 b'' $\pm$ 0.000
C2S2	0.03 b $\pm$ 0.000	0.03 b' $\pm$ 0.003	0.03 b'' $\pm$ 0.003
C2S3	0.03 b $\pm$ 0.003	0.03 b' $\pm$ 0.003	0.03 b'' $\pm$ 0.003
C2S4	0.04 b $\pm$ 0.006	0.03 b' $\pm$ 0.003	0.03 b'' $\pm$ 0.003
C2S5	0.03 b $\pm$ 0.000	0.03 b' $\pm$ 0.003	0.03 b'' $\pm$ 0.000
C3S1	0.03 b $\pm$ 0.003	0.03 b' $\pm$ 0.003	0.04 b'' $\pm$ 0.003
C3S2	0.04 b $\pm$ 0.003	0.04 b' $\pm$ 0.003	0.03 b'' $\pm$ 0.000
C3S3	0.03 b $\pm$ 0.000	0.03 b' $\pm$ 0.000	0.03 b'' $\pm$ 0.000
C3S4	0.03 b $\pm$ 0.000	0.03 b' $\pm$ 0.000	0.04 b'' $\pm$ 0.000
C3S5	0.04 b $\pm$ 0.003	0.03 b' $\pm$ 0.003	0.03 b'' $\pm$ 0.003

Means (value $\pm$ standard error) with different letters within the same column indicate significant differences using Tukey's test with $p \leq 0.05$. Small letters, small letters with ', and small letters with '' indicate mean comparison at forty, eighty, and one hundred and twenty days incubation, respectively.

At 40 DAI, 80 DAI, and 120 DAI, the combined use of Calciprill and sodium silicate significantly reduced exchangeable Fe^{2+} and Mn^{2+} compared with soil only (C0S0) (Tables 6 and 7). This is because these amendments increased soil pH to facilitate exchangeable Fe^{2+}, reacting with OH^- to form insoluble Fe hydroxides [17,38]. The C3S5 treatment demonstrated the lowest exchangeable Mn^{2+} at 40 DAI (2.94 ppm) and 120 DAI (2.45 ppm), suggesting that C3S5 is the most suitable combination to suppress exchangeable Mn^{2+} because of the significant differences in pH_{KCl}. A significant increase in soil pH transforms divalent Mn into oxide fractions via oxidation to reduce exchangeable Mn^{2+} [39].

Table 6. Mean soil exchangeable iron in relation to combined use of Calciprill and sodium silicate at forty, eighty, and one hundred and twenty days incubation.

Treatments	Soil Exchangeable Fe^{2+} (ppm)		
	40 Days	80 Days	120 Days
C0S0	418.4 a $\pm$ 28.9	332.4 a' $\pm$ 7.3	411.7 a'' $\pm$ 21.2
C1S1	245.3 b $\pm$ 8.1	191.6 bc' $\pm$ 5.7	249.3 bc'' $\pm$ 16.8
C1S2	172.5 b $\pm$ 9.2	187.9 bc' $\pm$ 9.9	239.6 bc'' $\pm$ 16.7
C1S3	171.7 b $\pm$ 12.0	170.8 bc' $\pm$ 17.9	252 bc'' $\pm$ 25.3
C1S4	230.1 b $\pm$ 18.2	207.8 bc' $\pm$ 20.2	265 bc'' $\pm$ 8.6
C1S5	203.2 b $\pm$ 8.7	215.1 bc' $\pm$ 28.3	284.2 bc'' $\pm$ 13.4
C2S1	182.5 b $\pm$ 12.2	148.2 c' $\pm$ 8.4	243.1 bc'' $\pm$ 11.9
C2S2	183.6 b $\pm$ 4.3	147.7 c' $\pm$ 7.1	282.5 bc'' $\pm$ 5.5
C2S3	221.5 b $\pm$ 11.9	178.1 bc' $\pm$ 4.5	262.2 bc'' $\pm$ 5.0
C2S4	193.5 b $\pm$ 35.5	221.8 bc' $\pm$ 35.5	275.1 bc'' $\pm$ 9.7
C2S5	213.7 b $\pm$ 33.2	203.2 bc' $\pm$ 5.3	307.5 b'' $\pm$ 33.7
C3S1	158.5 b $\pm$ 0.8	148.7 c' $\pm$ 10.2	277.9 bc'' $\pm$ 45.5
C3S2	180.1 b $\pm$ 14.9	151.9 c' $\pm$ 9.6	248.6 bc'' $\pm$ 59.3
C3S3	175.7 b $\pm$ 30.6	200.3 bc' $\pm$ 23.0	233.7 bc'' $\pm$ 12.7
C3S4	212.8 b $\pm$ 20.0	227.0 bc' $\pm$ 38.1	211.7 c'' $\pm$ 5.5
C3S5	149.3 b $\pm$ 4.5	260.2 ab' $\pm$ 0.5	279 bc'' $\pm$ 35.1

Means (value $\pm$ standard error) with different letters within the same column indicate significant differences using Tukey's test with $p \leq 0.05$. Small letters, small letters with ', and small letters with '' indicate mean comparison at forty, eighty, and one hundred and twenty days incubation, respectively.

Table 7. Mean soil exchangeable manganese in relation to combined use of Calciprill and sodium silicate at forty, eighty, and one hundred and twenty days incubation.

Treatments	Soil Exchangeable Mn^{2+} (ppm)		
	40 Days	**80 Days**	**120 Days**
C0S0	4.65 a $\pm$ 0.25	4.33 ab' $\pm$ 0.43	3.93 a'' $\pm$ 0.18
C1S1	4.08 ab $\pm$ 0.17	4.44 ab' $\pm$ 0.14	3.33 abc'' $\pm$ 0.18
C1S2	4.00 ab $\pm$ 0.18	4.11 ab' $\pm$ 0.22	3.25 abc'' $\pm$ 0.14
C1S3	3.13 bc $\pm$ 0.11	3.75 ab' $\pm$ 0.11	3.10 bcd'' $\pm$ 0.06
C1S4	3.13 bc $\pm$ 0.09	5.57 b' $\pm$ 0.07	3.04 bcd'' $\pm$ 0.08
C1S5	3.11 bc $\pm$ 0.15	3.60 ab' $\pm$ 0.1	2.93 cd'' $\pm$ 0.17
C2S1	3.76 abc $\pm$ 0.14	2.46 ab' $\pm$ 0.13	3.51 abc'' $\pm$ 0.31
C2S2	3.56 bc $\pm$ 0.07	4.2 ab' $\pm$ 0.16	3.47 abc'' $\pm$ 0.13
C2S3	3.10 bc $\pm$ 0.05	3.77 ab' $\pm$ 0.18	3.06 bcd'' $\pm$ 0.14
C2S4	3.29 bc $\pm$ 0.25	3.91 ab' $\pm$ 0.14	2.82 cd'' $\pm$ 0.06
C2S5	3.21 bc $\pm$ 0.54	3.87 ab' $\pm$ 0.11	2.99 bcd'' $\pm$ 0.18
C3S1	3.34 abc $\pm$ 0.16	4.61 a' $\pm$ 0.10	3.70 ab'' $\pm$ 0.03
C3S2	3.22 bc $\pm$ 0.05	4.39 ab' $\pm$ 0.04	3.33 abc'' $\pm$ 0.03
C3S3	3.29 bc $\pm$ 0.08	3.83 ab' $\pm$ 0.17	3.48 abc'' $\pm$ 0.12
C3S4	3.10 bc $\pm$ 0.10	3.65 ab' $\pm$ 0.31	2.79 cd'' $\pm$ 0.08
C3S5	2.94 c $\pm$ 0.04	3.66 ab' $\pm$ 0.29	2.45 d'' $\pm$ 0.09

Means (value $\pm$ standard error) with different letters within the same column indicate significant differences using Tukey's test with $p \leq 0.05$. Small letters, small letters with ', and small letters with '' indicate mean comparison at forty, eighty, and one hundred and twenty days incubation, respectively.

3.3. Combined Use of Calciprill and Sodium Silicate on Exchangeable Ammonium, Available Nitrate, and Available Phosphorus

At 40 DAI, exchangeable NH_4^+ in the soils with Calciprill and sodium silicate (especially C3S3, C3S4, and C3S5) significantly increased and ranged from 48.57 ppm to 52.30 ppm compared with the exchangeable NH_4^+ (32.22 ppm) of soil only (C0S0) (Table 8). This was partly due to the significant increase in the soil pH following the combined use of the Calciprill and sodium silicate. According to Bikley et al. [40], increased soil pH improves the transformation of organic N into NH_4^+ through enhanced mineralization, suggesting that higher rates of Calciprill and sodium silicate can increase soil NH_4^+ availability. This was possible because the amendments significantly improved the soil ECEC, thus resulting in higher soil exchangeable NH_4^+ retention because of the increased number of negatively charged sites of soil. This finding is consistent with those Gasser [41] and Avnimelech and Laher [42], who reported that soil CEC is the most important factor that reduces NH_4^+ loss through NH_3 volatilization because soils with higher CEC are able to retain exchangeable NH_4^+ from being transformed by, for example, urease. Urease is the enzyme that catalyzes NH_4^+ transformation to NH_3 emission. There were no significant differences among the treatments with Calciprill and sodium silicate for exchangeable NH_4^+ compared with soil only (C0S0) at 80 DAI and 120 DAI (Table 8) because both of the amendments had low exchangeable NH_4^+. Thus, application of nitrogen-based fertilizers and organic materials to significantly increase soil exchangeable NH_4^+ in agricultural systems which include liming programs using Calciprill and sodium silicate is essential.

At 40 DAI and 80 DAI, the combined use of Calciprill and sodium silicate significantly improved soil available NO_3^- compared with soil only (C0S0) because of the increase in soil pH which improved the mineralization of organic N into inorganic NO_3^- [43]. However, it was observed that soil available NO_3^- significantly increased in the soils with lower rates of Calciprill and sodium silicate, whereas exchangeable NH_4^+ was significantly higher in the soils with higher application rates of Calciprill and sodium silicate (Tables 8 and 9). This was partly due to the significant difference in soil pH and $CaCO_3$ contents among those treatments, because lower pH and $CaCO_3$ transformed exchangeable NH_4^+ to NO_3^- through nitrification [36,43]. Moreover, the higher soil NH_4^+ retention was due to the higher soil ECEC. This contributed to lower available NO_3^- because of reduced nitrification.

This finding corroborates the findings of Ferguson and Pepper [44] and MacKown and Tucker [45], who also reported that increased soil CEC prevents exchangeable NH_4^+ from being transformed into available NO_3^- through nitrification. At 120 DAI, available NO_3^- of the soils with and without Calciprill and sodium silicate were similar (Table 9) because of the reduced transformation of soil exchangeable NH_4^+ to available NO_3^-. Some of the exchangeable NH_4^+ might have been lost through NH_3 volatilization. Moreover, both of the amendments were lower in available NO_3^- compared with the soil, suggesting that application of nitrogen-based fertilizers is needed to increase soil available NO_3^-.

Table 8. Mean soil exchangeable ammonium in relation to combined use of Calciprill and sodium silicate at forty, eighty, and one hundred and twenty days incubation.

Treatments	Soil Exchangeable NH_4^+ (ppm)		
	40 Days	80 Days	120 Days
C0S0	32.22 cde $\pm$ 0.81	28.02 ab' $\pm$ 1.62	26.15 ab'' $\pm$ 3.37
C1S1	25.22 e $\pm$ 1.62	26.15 b' $\pm$ 1.87	20.55 b'' $\pm$ 0.93
C1S2	23.35 de $\pm$ 2.47	26.15 b' $\pm$ 1.87	23.35 ab'' $\pm$ 0.93
C1S3	33.62 bcde $\pm$ 1.62	29.89 ab' $\pm$ 4.07	23.82 ab'' $\pm$ 0.81
C1S4	42.03 abc $\pm$ 3.24	29.89 ab' $\pm$ 0.93	24.28 ab'' $\pm$ 0.93
C1S5	42.03 abc $\pm$ 1.62	28.02 ab' $\pm$ 2.80	29.89 ab'' $\pm$ 4.07
C2S1	30.82 cde $\pm$ 1.62	26.15 ab' $\pm$ 2.47	21.48 ab'' $\pm$ 0.93
C2S2	29.89 cde $\pm$ 4.07	25.22 b' $\pm$ 1.62	23.35 ab'' $\pm$ 0.93
C2S3	42.03 abc $\pm$ 1.62	30.82 ab' $\pm$ 2.80	26.15 ab'' $\pm$ 0.93
C2S4	37.36 abcde $\pm$ 6.54	32.69 ab' $\pm$ 4.67	28.95 ab'' $\pm$ 2.47
C2S5	33.62 bcde $\pm$ 1.62	34.56 ab' $\pm$ 4.94	31.76 ab'' $\pm$ 1.87
C3S1	32.69 cde $\pm$ 2.47	23.35 b' $\pm$ 0.93	26.15 ab'' $\pm$ 2.47
C3S2	40.16 abcd $\pm$ 0.93	26.15 b' $\pm$ 0.93	29.89 ab'' $\pm$ 3.37
C3S3	48.57 ab $\pm$ 1.89	30.82 ab' $\pm$ 2.80	26.15 ab'' $\pm$ 2.47
C3S4	52.30 a $\pm$ 5.20	37.36 ab' $\pm$ 4.94	29.89 ab'' $\pm$ 0.93
C3S5	51.84 a $\pm$ 0.81	42.03 a' $\pm$ 1.62	32.69 a'' $\pm$ 3.37

Means (value $\pm$ standard error) with different letters within the same column indicate significant differences using Tukey's test with $p \leq 0.05$. Small letters, small letters with ', and small letters with '' indicate mean comparison at forty, eighty, and one hundred and twenty days incubation, respectively.

Table 9. Mean soil available nitrate in relation to combined use of Calciprill and sodium silicate at forty, eighty, and one hundred and twenty days incubation.

Treatments	Soil Available NO_3^- (ppm)		
	40 Days	80 Days	120 Days
C0S0	22.42 d $\pm$ 3.24	33.62 bcdef' $\pm$ 1.62	33.62 abc'' $\pm$ 1.62
C1S1	46.70 ab $\pm$ 5.20	44.83 ab' $\pm$ 1.62	51.84 a'' $\pm$ 5.66
C1S2	39.23 abcd $\pm$ 1.62	41.1 abc' $\pm$ 2.47	39.23 abc'' $\pm$ 4.28
C1S3	48.57 ab $\pm$ 5.20	32.69 bcdef' $\pm$ 2.47	32.22 abc'' $\pm$ 4.20
C1S4	26.15 cd $\pm$ 2.47	33.62 bcdef' $\pm$ 1.62	41.10 abc'' $\pm$ 5.68
C1S5	30.82 bcd $\pm$ 4.28	28.95 cdef' $\pm$ 2.47	37.36 abc'' $\pm$ 2.47
C2S1	55.11 a $\pm$ 3.37	47.63 a' $\pm$ 4.28	40.16 abc'' $\pm$ 4.67
C2S2	44.83 ab $\pm$ 1.62	25.22 ef' $\pm$ 0.00	32.69 abc'' $\pm$ 1.89
C2S3	45.77 ab $\pm$ 4.07	39.23 abc' $\pm$ 1.62	44.83 ab'' $\pm$ 5.83
C2S4	39.23 abcd $\pm$ 5.83	21.48 f' $\pm$ 1.87	23.35 c'' $\pm$ 2.47
C2S5	49.04 ab $\pm$ 0.81	27.09 def' $\pm$ 3.37	35.49 abc'' $\pm$ 2.47
C3S1	46.70 ab $\pm$ 4.94	45.77 ab' $\pm$ 4.94	35.02 abc'' $\pm$ 7.28
C3S2	42.03 abcd $\pm$ 0.00	37.36 abcde' $\pm$ 1.87	39.23 abc'' $\pm$ 1.62
C3S3	37.36 abcd $\pm$ 3.74	20.55 f' $\pm$ 0.93	28.95 bc'' $\pm$ 1.87
C3S4	32.22 bcd $\pm$ 2.43	23.35 f' $\pm$ 3.74	33.62 abc'' $\pm$ 4.28
C3S5	35.03 bcd $\pm$ 0.81	25.22 ef' $\pm$ 2.80	28.02 bc'' $\pm$ 1.62

Means (value $\pm$ standard error) with different letters within the same column indicate significant differences using Tukey's test with $p \leq 0.05$. Small letters, small letters with ', and small letters with '' indicate mean comparison at forty, eighty, and one hundred and twenty days incubation, respectively.

At 40 DAI, 80 DAI, and 120 DAI, the soils with the amendments significantly enhanced soil available P compared with soil only (C0S0) (Table 10). The increase in available P availability was due to mineralization of organic P into inorganic available P, because the improved soil pH stimulated the soil microbes to decompose the organic materials in the soil to release P [46,47]. This was due to the increased soil pH from the initial pH_{KCl} of 3.94 to a pH range of 7.69 to 8.21 after applying the Calciprill and sodium silicate, because they significantly reduced exchangeable Al^{3+}, Fe^{2+}, and Mn^{2+}. For example, the Calciprill and sodium silicate significantly reduced soil exchangeable Al^{3+} below the threshold of 0.8 $cmol_{(+)}$ kg^{-1} to alleviate Al and Fe toxicity [4]. This suggests that the soil pH following the combined use of Calciprill and sodium silicate unlocked P fixed by Al, Fe, and Mn [5,17,37]. Thus, the lower available P for the soil without Calciprill and sodium silicate (C0S0) was due to the reaction between P and soluble Fe, Al, and Mn ions, suggesting that soil pH is the dominant factor in controlling P availability [38].

Table 10. Mean soil available phosphorus in relation to combined use of Calciprill and sodium silicate at forty, eighty, and one hundred and twenty days incubation.

6PTTreatments	Soil Available P (ppm)		
	40 Days	**80 Days**	**120 Days**
C0S0	0.63 c ± 0.01	0.52 b′ ± 0.08	0.93 b″ ± 0.09
C1S1	0.86 abc ± 0.07	1.04 a′ ± 0.09	1.26 a″ ± 0.04
C1S2	0.69 bc ± 0.06	1.00 ab′ ± 0.06	1.28 a″ ± 0.11
C1S3	0.77 abc ± 0.10	1.09 a′ ± 0.05	1.10 ab″ ± 0.05
C1S4	0.84 abc ± 0.09	1.04 a′ ± 0.05	1.32 a″ ± 0.02
C1S5	0.68 bc ± 0.08	0.97 ab′ ± 0.10	1.27 a″ ± 0.03
C2S1	0.84 abc ± 0.05	1.20 a′ ± 0.11	1.37 a″ ± 0.01
C2S2	0.86 abc ± 0.07	1.16 a′ ± 0.05	1.47 a″ ± 0.12
C2S3	1.00 abc ± 0.11	0.94 ab′ ± 0.16	1.34 a″ ± 0.16
C2S4	0.75 abc ± 0.06	1.22 a′ ± 0.18	1.22 a″ ± 0.08
C2S5	0.85 abc ± 0.05	1.05 a′ ± 0.08	1.48 a″ ± 0.03
C3S1	0.92 abc ± 0.10	1.06 a′ ± 0.15	1.14 ab″ ± 0.01
C3S2	0.96 abc ± 0.04	1.19 a′ ± 0.11	1.17 ab″ ± 0.13
C3S3	1.08 ab ± 0.03	1.20 a′ ± 0.12	1.33 a″ ± 0.17
C3S4	1.18 a ± 0.16	1.08 a′ ± 0.10	1.10 ab″ ± 0.12
C3S5	1.16 a ± 0.08	1.18 a′ ± 0.10	1.23 a″ ± 0.16

Means (value ± standard error) with different letters within the same column indicate significant differences using Tukey's test with $p \leq 0.05$. Small letters, small letters with ′, and small letters with ″ indicate mean comparison at forty, eighty, and one hundred and twenty days incubation, respectively.

In addition, the increase in available P was partly due to ability of the Si to mobilize P from the exchangeable sites of the soil–Fe interaction. Schaller et al. [34] reported that an increase in Si availability in soils correlates positively with P mobilization. Release of P from sorption sites of soil iron minerals is related to a stronger bonding affinity of Si to soil minerals compared with P. Thus, Si mobilizes P by replacing P on the soil exchangeable sites, resulting in increased P availability [34,48]. Moreover, the significant increase in the available P via sodium silicate application was partly due to the significant decrease in exchangeable Fe^{2+} and Al^{3+}. Reduced exchangeable Al^{3+}, Fe^{2+}, and Mn^{2+} also decreases P fixation because balanced use of Si increases soil pH to reduce re-sorption of P onto hydrolyzed Al, Fe, and Mn ions. Silicon is capable of outcompeting to prevent P from being sorbed on the surfaces of Al, Fe, and Mn minerals [49].

It is believed that P availability is constrained by increased exchangeable cation concentrations (especially exchangeable Ca). This occurs when soil is limed above pH 7, because available P reacts with $CaCO_3$ to form Ca–P compounds. Phosphate solubility decreases with increasing soil pH, followed by formation of precipitated P compounds via crystallization [7]. It was possible for P to react with Na to form soluble Na–P following application of sodium silicate, but this reaction does not significantly affect P availability [50]. This explains why P availability reaches its maximum when the soil pH is between 6.5

and 7. At 40 DAI, 80 DAI, and 120 DAI, it was observed that available P was consistently higher in soils with the highest rates of Calciprill and sodium silicate (C3S5) compared with soil only (C0S0), although the soils with the Calciprill and sodium silicate were alkaline (Table 10). This suggests that P fixation is significantly higher in acidic soils compared with alkaline soils [51].

3.4. Combined Use of Calciprill and Sodium Silicate on Electrical Conductivity, Exchangeable Base Cations, and Effective Cation Exchange Capacity

At 40 DAI, 80 DAI, and 120 DAI, the soil electrical conductivity was significantly affected by combined use of Calciprill and sodium silicate compared with soil only (C0S0) (Table 11), suggesting that the sodium silicate is salty and it must not be excessively used. According to USDA [52], the threshold of soil electrical conductivity to impede crop growth and microorganism activities is 4.0 dS m^{-1}. Based on Table 11, the EC of the combined use of Calciprill and sodium silicate did not exceed this threshold and was rather within the salinity class of non-saline (0 to 2 dS m^{-1}), suggesting that the application rates of Calciprill and sodium silicate used in this present study were acceptable for crop cultivation.

Table 11. Mean soil electrical conductivity in relation to combined use of Calciprill and sodium silicate at forty, eighty, and one hundred and twenty days incubation.

Treatments	Soil EC (dS m^{-1})		
	40 Days	**80 Days**	**120 Days**
C0S0	0.05 e ± 0.01	0.13 b′ ± 0.02	0.13 c″ ± 0.01
C1S1	0.44 cd ± 0.01	0.46 a′ ± 0.01	0.50 ab″ ± 0.004
C1S2	0.50 bcd ± 0.01	0.48 a′ ± 0.03	0.45 b″ ± 0.02
C1S3	0.50 bcd ± 0.02	0.45 a′ ± 0.02	0.45 b″ ± 0.01
C1S4	0.53 ab ± 0.02	0.47 a′ ± 0.03	0.54 a″ ± 0.02
C1S5	0.53 ab ± 0.02	0.48 a′ ± 0.01	0.54 ab″ ± 0.003
C2S1	0.46 bcd ± 0.01	0.56 a′ ± 0.05	0.49 ab″ ± 0.01
C2S2	0.47 bcd ± 0.02	0.55 a′ ± 0.03	0.46 ab″ ± 0.01
C2S3	0.47 bcd ± 0.01	0.44 a′ ± 0.02	0.49 ab″ ± 0.01
C2S4	0.59 a ± 0.03	0.55 a′ ± 0.05	0.49 ab″ ± 0.01
C2S5	0.52 abc ± 0.02	0.49 a′ ± 0.04	0.51 ab″ ± 0.01
C3S1	0.43 d ± 0.01	0.57 a′ ± 0.04	0.48 ab″ ± 0.05
C3S2	0.48 bcd ± 0.01	0.53 a′ ± 0.02	0.48 ab″ ± 0.02
C3S3	0.47 bcd ± 0.02	0.46 a′ ± 0.01	0.46 ab″ ± 0.02
C3S4	0.54 ab ± 0.01	0.53 a′ ± 0.05	0.54 ab″ ± 0.02
C3S5	0.54 ab ± 0.02	0.51 a′ ± 0.01	0.53 ab″ ± 0.02

Means (value ± standard error) with different letters within the same column indicate significant differences using Tukey's test with $p \leq 0.05$. Small letters, small letters with ′, and small letters with ″ indicate mean comparison at forty, eighty, and one hundred and twenty days incubation, respectively.

At 40 DAI, 80 DAI, and 120 DAI, the combined use of Calciprill and sodium silicate significantly increased exchangeable K$^+$, Ca^{2+}, Mg^{2+}, and Na$^+$ compared with C0S0 (Figures 1–4) because the inherent contents of K$^+$, Ca^{2+}, Mg^{2+}, and Na$^+$ of the amendments increased the soil base saturation. Cai et al. [35] reported that base saturation of soils can be increased with the addition of amendments that are high in base saturation. The soils with the highest rates of Calciprill and sodium silicate (C3S5) demonstrated the highest exchangeable K$^+$ availability at 40 DAI (35.33 ppm), 80 DAI (22.40 ppm), and 120 DAI (28.13 ppm) (Figure 1), suggesting C3S5 is the most suitable combination of Calciprill and sodium silicate for exchangeable K$^+$ availability. At 40 DAI, 80 DAI, and 120 DAI, unlike exchangeable K$^+$, exchangeable Ca^{2+} and Mg^{2+} did not increase with the increasing rates of both amendments (Figures 2 and 3) because of the incomplete dissolution of Calciprill, unlike sodium silicate which is highly soluble in water, although it is not high in Ca and Mg compared with the soil. Soil exchangeable Na$^+$ was significantly affected by the increasing amount of the sodium silicate compared with soil only (C0S0) at 40 DAI, 80 DAI, and 120 DAI (Figure 4). This suggests that the application rates of sodium sili-

cate can significantly influence soil exchangeable Na^+ because of its inherent Na^+ in the sodium silicate.
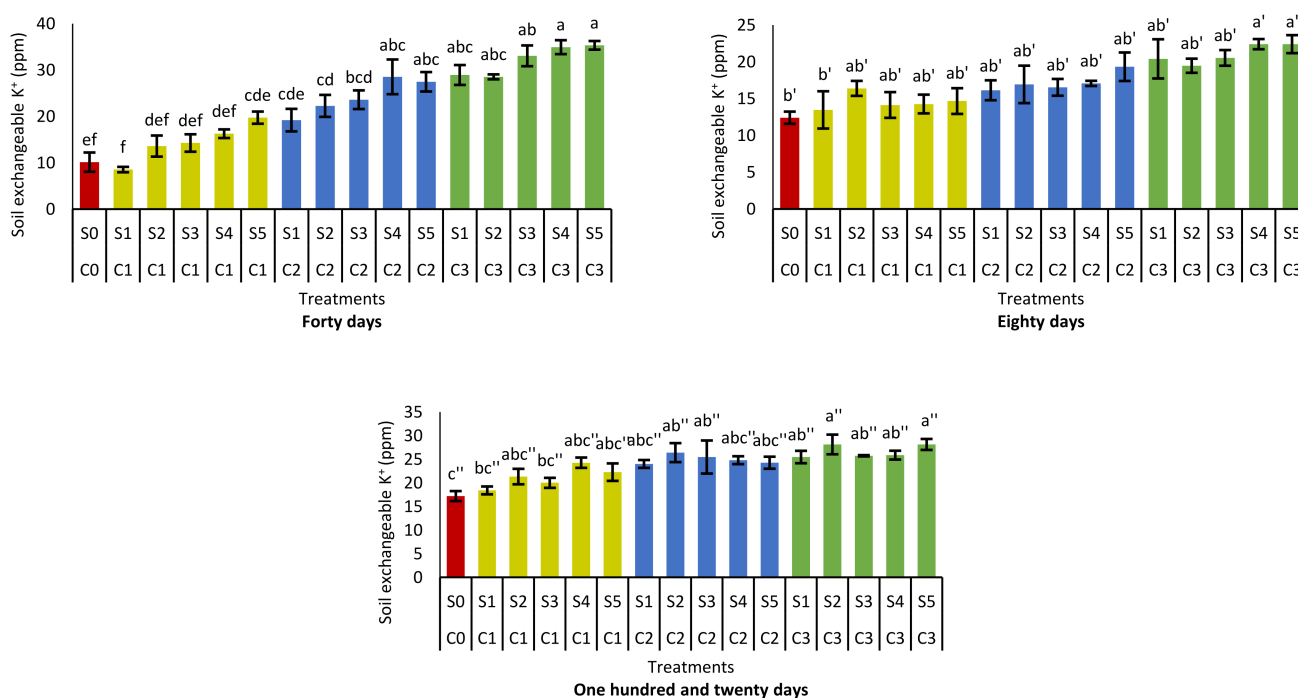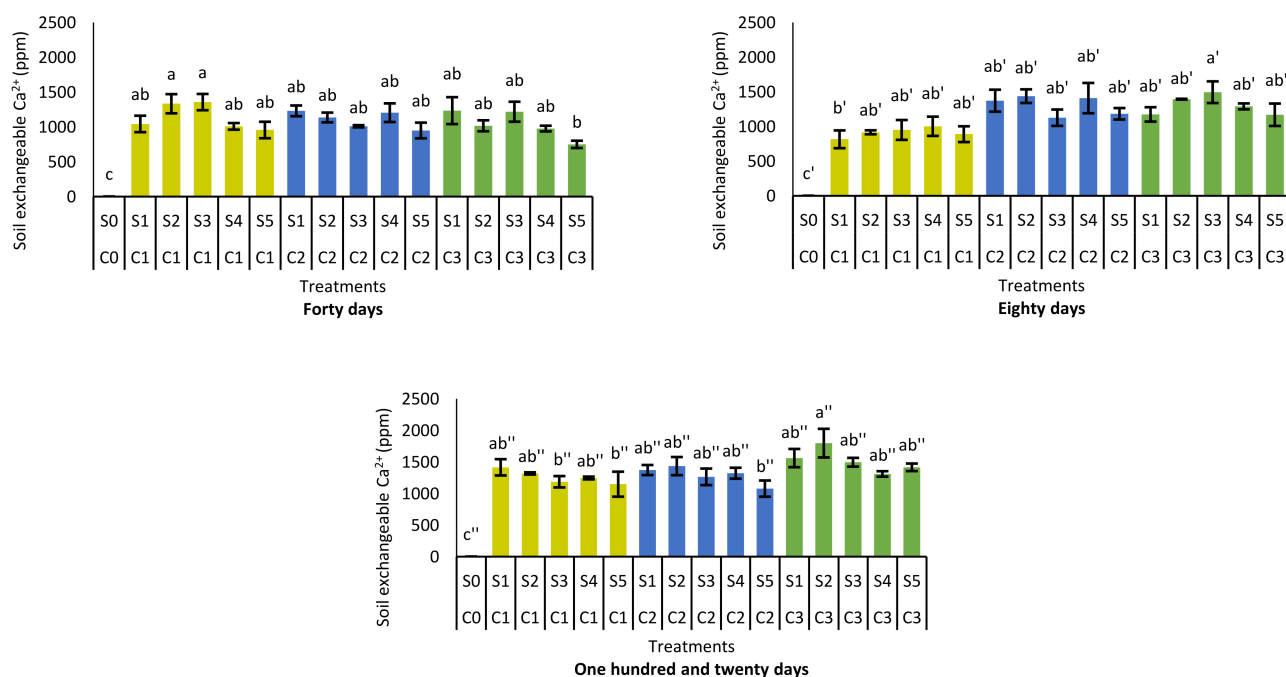

Figure 1. Soil exchangeable potassium in relation to combined use of Calciprill and sodium silicate at forty, eighty, and one hundred and twenty days incubation. Different letters indicate significant mean differences using Tukey's HSD test at $p \leq 0.05$. The error bars refer to $\pm$ standard error of three replicates. Small letters, small letters with ', and small letters with '' indicate mean comparison at forty, eighty, and one hundred and twenty days incubation, respectively.
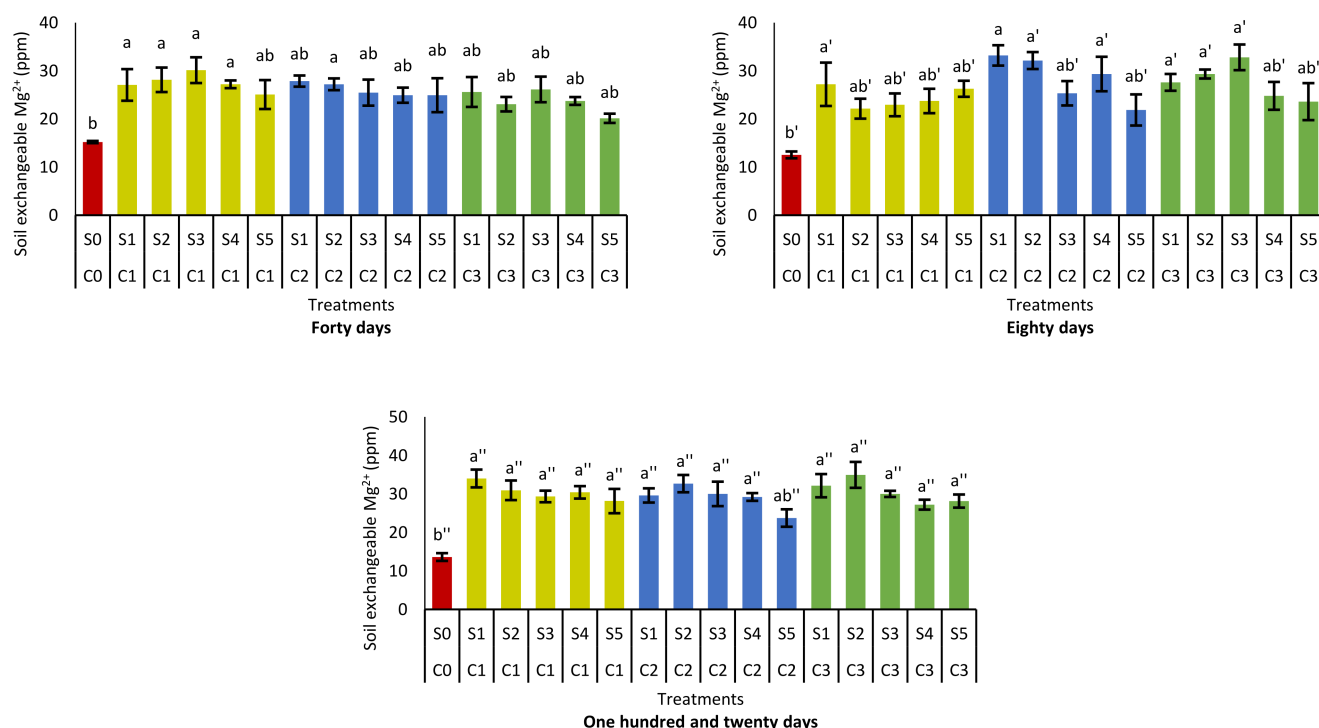

Figure 2. Soil exchangeable calcium in relation to combined use of Calciprill and sodium silicate at forty, eighty, and one hundred and twenty days incubation. Different letters indicate significant mean differences using Tukey's HSD test at $p \leq 0.05$. The error bars refer to $\pm$ standard error of three replicates. Small letters, small letters with ', and small letters with '' indicate mean comparison at forty, eighty, and one hundred and twenty days incubation, respectively.
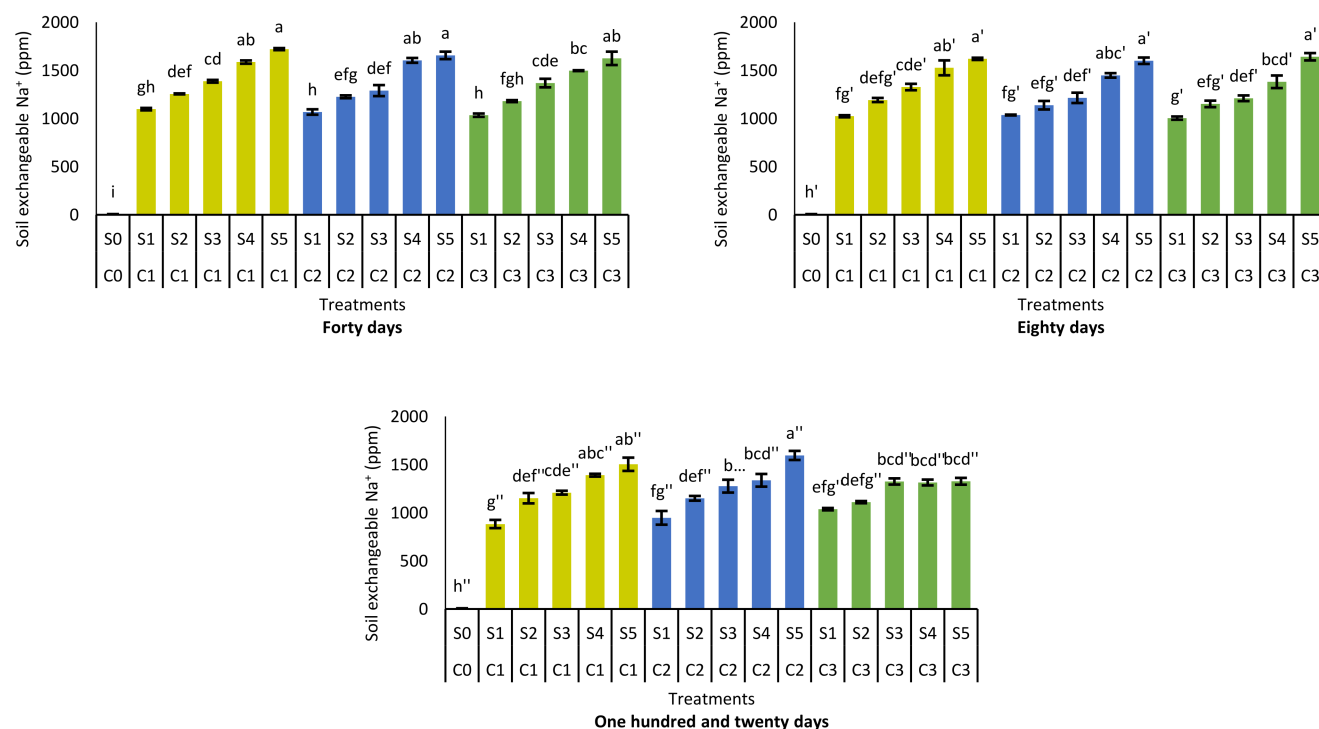
Figure 3. Soil exchangeable magnesium in relation to combined use of Calciprill and sodium silicate at forty, eighty, and one hundred and twenty days incubation. Different letters indicate significant mean differences using Tukey's HSD test at $p \leq 0.05$. The error bars refer to $\pm$ standard error of three replicates. Small letters, small letters with ', and small letters with " indicate mean comparison at forty, eighty, and one hundred and twenty days incubation, respectively.

Figure 4. Soil exchangeable sodium in relation to combined use of Calciprill and sodium silicate at forty, eighty, and one hundred and twenty days incubation. Different letters indicate significant mean differences using Tukey's HSD test at $p \leq 0.05$. The error bars refer to $\pm$ standard error of three replicates. Small letters, small letters with ', and small letters with " indicate mean comparison at forty, eighty, and one hundred and twenty days incubation, respectively.

At 40 DAI, 80 DAI, and 120 DAI, ECEC significantly increased with the combined use of Calciprill and sodium silicate compared with soil only (C0S0) (Table 12), and this relates to the amendments' ability to increase soil pH. Aprile and Lorandi [53] reported that soil CEC correlates with ECEC when soil pH is greater than 8.3 because soil exchangeable acidity is considered negligible. Sdiri et al. [54] reported that soils that are saturated with higher $CaCO_3$, rather than Al_2O_3 and Fe_2O_3, have higher ECEC because of the increased number of negatively charged sites on the surface of $CaCO_3$. In other words, increased soil pH and surface charge on soil minerals through Calciprill application improved the soil ECEC [55].

Table 12. Mean soil Effective Cation Exchange Capacity in relation to combined use of Calciprill and sodium silicate at forty, eighty, and one hundred and twenty days incubation.

Treatments	Soil ECEC ($cmol_{(+)} kg^{-1}$)		
	40 Days	80 Days	120 Days
C0S0	1.77 e $\pm$ 0.10	1.43 f' $\pm$ 0.02	1.74 d″ $\pm$ 0.07
C1S1	15.90 d $\pm$ 0.70	13.94 e' $\pm$ 0.61	16.00 c″ $\pm$ 1.05
C1S2	18.49 abcd $\pm$ 0.72	15.86 cde' $\pm$ 0.09	17.79 abc″ $\pm$ 0.59
C1S3	19.76 ab $\pm$ 0.65	17.14 bcdef' $\pm$ 1.05	17.88 abc″ $\pm$ 0.32
C1S4	19.94 ab $\pm$ 0.27	19.28 abcd' $\pm$ 1.02	19.60 abc″ $\pm$ 0.01
C1S5	20.75 a $\pm$ 0.69	19.57 abc' $\pm$ 0.60	20.14 a″ $\pm$ 0.70
C2S1	16.39 cd $\pm$ 0.31	16.73 bcde' $\pm$ 0.83	16.29 bc″ $\pm$ 1.01
C2S2	17.29 bcd $\pm$ 0.43	17.94 abcde' $\pm$ 0.71	18.54 abc″ $\pm$ 0.82
C2S3	17.34 bcd $\pm$ 0.51	17.10 bcde' $\pm$ 0.89	18.69 abc″ $\pm$ 1.26
C2S4	20.96 a $\pm$ 0.43	20.73 ab' $\pm$ 1.05	19.54 abc″ $\pm$ 0.29
C2S5	20.20 ab $\pm$ 0.57	19.81 abc' $\pm$ 0.78	20.64 a″ $\pm$ 0.82
C3S1	16.04 cd $\pm$ 0.93	15.43 de' $\pm$ 0.65	18.17 abc″ $\pm$ 0.71
C3S2	16.27 cd $\pm$ 0.41	17.84 abcde' $\pm$ 0.32	19.92 ab″ $\pm$ 0.98
C3S3	18.94 abc $\pm$ 0.76	19.05 abcd' $\pm$ 0.99	20.17 a″ $\pm$ 0.58
C3S4	18.97 abc $\pm$ 0.22	19.55 abc' $\pm$ 0.77	19.05 abc″ $\pm$ 0.16
C3S5	18.69 abcd $\pm$ 0.63	21.32 a' $\pm$ 0.93	19.93 ab″ $\pm$ 0.48

Means (value $\pm$ standard error) with different letters within the same column indicate significant differences using Tukey's test with $p \leq 0.05$. Small letters, small letters with ', and small letters with ″ indicate mean comparison at forty, eighty, and one hundred and twenty days incubation, respectively.

The effects of the combined use of Calciprill and sodium silicate on ECEC were not consistent because of the incomplete dissolution of Calciprill (Table 12). The incomplete dissolution of Calciprill suggests that this amendment can provide more negatively charged surface area for adsorbing more exchangeable cations to increase the ECEC of the soil. This finding is comparable to that of Zhao et al. [56] who also reported that $CaCO_3$ can regulate the ECEC of alkaline soils. However, with time, continued dissolution of Calciprill in the soils can reduce ECEC because $CaCO_3$ decomposes into exchangeable Ca^{2+} and CO_3^{2-} to neutralize immobilized H^+, thus reducing negatively charged surface area for exchangeable cations adsorption [36]. The continued dissolution of $CaCO_3$ increases soil pH buffering capacity. At soil pH 8, Bowman et al. [57] reported that dissolution of $CaCO_3$ can significantly improve soil pH buffering capacity. Moreover, at 40 DAI, 80 DAI, and 120 DAI, with the same amount of Calciprill (C1, C2, and C3, respectively), the ECEC of the soil with the highest rate of sodium silicate (S5) was significantly higher than with the lowest rate of sodium silicate (S1), suggesting that sodium silicate can improve soil ECEC.

4. Conclusions

Combined use of Calciprill and sodium silicate on Bekenu series (acid soil) improves its chemical properties via increased inorganic N, available P, electrical conductivity, exchangeable base cations (K, Ca, Mg, and Na), and ECEC. This is because the amendments increase soil pH to reduce exchangeable acidity, in addition to transforming soluble acidic cations (Al, Fe, and Mn) into insoluble and unreactive forms through neutralization and immobilization of exchangeable H^+. These findings suggest that combined use of Calciprill

and sodium silicate can increase the overall soil productivity. Nevertheless, because of the absence of plants and regular irrigation, this laboratory incubation study does not unravel the effects on plant–soil interactions and leaching. The most suitable combination is 7.80 g Calciprill and 9.26 g sodium silicate (C3S5) per one kilogram soil. The combined use of Calciprill and sodium silicate provides fundamental information for future greenhouse and field trials to determine the effects of the suitable combination of the amendments uncovered by this present study on soil health and crop productivity. Greenhouse and field trials are recommended to further evaluate the findings of this present laboratory incubation study.

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