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Organopolymer Based Liming Materials for Alleviating Acidity in Acid Sulphate Soils of Kuttanad, India

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Acid sulphate soils of Kerala are characterized by extreme acidity and toxic concentrations of aluminium (Al^{3+}) and iron (Fe^{2+}/Fe^{3+}), which severely restrict crop growth and productivity. A laboratory incubation was undertaken to evaluate the efficiency of organopolymer and silicate-

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based lime formulations in ameliorating soil acidity and reducing Al and Fe toxicity in acid sulphate soils. The lime formulation comprising of different lime sources (burnt lime, calcium carbonate, dolomite, and phosphogypsum) combined with organic polymers (fulvic acid, polymaleic acid, and polyfumaric acid) and silicate mixture were applied to acid sulphate soil incubated for 90 days under submerged condition. Changes in soil pH (water and $CaCl_2$), exchangeable acidity, and exchangeable H^+ and Al^{3+} were determined at 15 day intervals up to 90 days. Results revealed a significant improvement in soil reaction across all lime formulation–treated soils compared to the control. Among the treatments, burnt lime + fulvic acid + silicate mixture (T1) recorded the highest pH in both water and $CaCl_2$ extracts, indicating rapid and sustained neutralization of acidity. This was further supported by a marked reduction in exchangeable acidity from 2.23 to 1.80 meq 100 g^{-1}, exchangeable Al^{3+} from 1.62 to 1.35 meq 100 g^{-1}, and exchangeable H^+ from 0.62 to 0.29 meq 100 g^{-1}, accompanied by an increase in pH (H_2O) from 4.71 to 5.30 and pH ($CaCl_2$) from 4.36 to 4.97 between the 15th and 90th day of incubation, confirming the effective amelioration of both active and potential acidity. The synergistic effect of fulvic acid and silicate mixture enhanced lime reactivity through complexation, chelation, and hydroxyl ion release, facilitating prolonged pH stabilization.

Keywords: Acid sulphate soil; fulvic acid; silicate mixture; organopolymer compounds; lime formulations; aluminium toxicity; soil pH.

1. INTRODUCTION

Soils of Kerala are predominantly acidic (90%) having low level of plant nutrients and cation exchange capacity (CEC) with weak retention capacity of bases applied as fertilizers or as amendments. As much as 54% of soils are extremely to strongly acidic (pH 3.5-5.5) requiring amelioration with lime to alleviate acidity. Acid sulphate soils containing metal sulfides are extremely acidic (pH < 3.5), which directly affects the growth of plants as a result of aluminium (Al) and iron (Fe) toxicity and indirectly decreases the availability of phosphorus (P) and other nutrients. The problem of Fe and Al toxicity creates soil stress and high yielding varieties could perform to a level of only 50% of their potential yield. Subsoil acidity, as characterized by low calcium (Ca) and high Al at depths below the plough layer, is also restricting root growth and activity, crop growth and production.

Kuttanad, the rice bowl of Kerala, is a unique agricultural tract lying 0.6 to 2.2 m below the mean sea level and has a geographic area of 854 sq. km. Kari soils of Kuttanad extending in an area of 9000 ha are affected by severe acidity and periodic saline water inundation with consequent accumulation of soluble salts. Fe and Al toxicity are also an important constraint for rice production because the low pH dissolves Fe and Al in the soil and develops toxicity symptoms. For amelioration of acidity use of liming materials such as shell lime, calcite and dolomite can be undertaken. But the quality of these conventional liming materials are highly variable and application rates are large and are expensive. Besides this, conventional liming of the top soil may have little effect on subsoil acidity because the downward movement of lime is very slow. By applying lime and organic compounds together to the top soil, formation of calcium fulvinate occurs and more Ca would be moved to the subsoil. Polymeric compounds like natural polymers of fulvic acid, humic acid, lignin etc., synthetic poly-carboxylic acids viz., poly maleic acid, poly fumaric acid, poly maleic acrylic acid and silicate polymers *viz.*, Ca, potassium (K) and sodium (Na) silicates can complex Fe and Al and when applied along with lime significantly reduce the application rates of liming materials and are also more effective in controlling subsoil acidity and Fe and Al toxicity. The aim of the study was to assess the potential of organo-polymer-based lime formulations to alleviate acidity in the acid sulphate soils of Kerala.

2. MATERIALS AND METHODS

A laboratory incubation study was conducted in 2021 at the College of Agriculture, Vellayani, under submerged conditions for 90 days using acid sulphate soils collected from AEU-4 (Kuttanadu) to assess the effectiveness and potential of different organo-polymer and silicate-based lime formulations in alleviating soil acidity and Fe and Al toxicity. The liming materials used were: 1) Burnt lime (BL), 2) $CaCO_3$, 3) Dolomite, 4) $CaCO_3$ + Phosphogypsum and Organo polymers used were: 1) Fulvic acid (FA), 2) Polymaleic acid (PMA) and 3) Poly fumaric acid

(PFA). Silicate mixture consists of calcium silicate + potassium silicate + sodium silicate.

2.1 Preparation of Lime Formulations

The calcium silicate, potassium silicate and sodium silicate were mixed in the ratio 2:1:1 in order to prepare silicate mixture. The polymer silicate mixtures were prepared by mixing polymers and silicate mixture in the ratio 0.5:1.5. Further the liming materials and polymer silicate mixture were mixed in the ratio 8:2 and the lime formulation were prepared.

2.2 Incubation Experiment

A laboratory incubation experiment was conducted for 90 days to access the effectiveness and potential of lime formulations in alleviating soil acidity, Fe & Al toxicity. Five kilograms of acid sulphate soil was taken in pots and the required quantity of each lime formulation was calculated based on soil pH and the calcium carbonate equivalence of the prepared formulations. The amount of each lime formulation necessary for neutralization was determined using the following equation:

$$\text{Quantity of liming material (Kg ha-1)} = \frac{\text{Quantity of pure CaCO3 required (Kg ha-1)}}{\text{\% CaCO3 equivalence of the liming material}} \times 100$$

Based on the soil pH, the required quantity of pure calcium carbonate was estimated to be 850 kg ha^{-1} (KAU POP, 2024). Using this value, the corresponding quantities of various lime formulations required for each treatment in the incubation study were calculated as follows:

- **T_1(BL+ FA+ SM):** 1.76 g 5 kg^{-1}
- **T_2(BL PMA+ SM):** 1.93 g 5 kg^{-1}
- **T_3 (BL+ PFA+ SM):** 1.91 g 5 kg^{-1}
- **T_4 ($CaCO_3$+ FA+ SM):** 2.40 g 5 kg^{-1}
- **T_5($CaCO_3$ + PMA+ SM):** 2.41 g 5 kg^{-1}
- **T_6 ($CaCO_3$ + PFA+ SM):** 2.56 g 5 kg^{-1}
- **T_7 ($CaCO_3$+PG+FA+SM):** 2.74 g 5 kg^{-1}
- **T_8 ($CaCO_3$+PG+PMA+SM):** 3.20 g 5 kg^{-1}
- **T_9 (Dolomite+ FA+ SM):** 1.83 g 5 kg^{-1}
- **T_{10} (Dolomite+ PMA+ SM):** 2.42 g 5 kg^{-1}
- **T_{11} ($CaCO_3$ alone):** 2.2 g 5 kg^{-1}
- **T_{12}(absolute control):** No lime

2.2.1 Soil sampling and analysis for the incubation experiment

Soil samples were collected on the 15th, 30th, 45th, 60th and 90th days of the incubation experiment to evaluate the efficacy and potential of various lime formulations in mitigating soil acidity and the toxic effects of Fe and Al. The collected samples were subsequently analyzed for soil chemical properties, including pH (in both water and $CaCl_2$ solution) using potentiometry (Jackson, 1973), exchangeable acidity, exchangeable H^+ and Al^{3+} using titrimetry (Yuan, 1959).

3. RESULTS

The results of the incubation study showed that the treatments had significant effect on soil pH (water and $CaCl_2$), exchangeable acidity, exchangeable H^+ and exchangeable Al^{3+}. The data were given in Tables 1,2,3,4 and 5.

3.1 Soil pH (Water)

A significant increase in soil pH was observed across all sampling intervals due to the application of lime formulations, compared to the absolute control. Overall, the pH of the soil showed a gradual increase from 15 to 90 days of incubation (Table 1). At each sampling interval, the lowest pH was consistently recorded in T_{12} (Absolute control), whereas the highest pH was observed in T_1 (BL + FA + SM). On 15th day of incubation, treatment T_1 exhibited the highest soil pH (4.71) which was found to be on par with T_4 (4.67), T_7 (4.65) and T_9 (4.64). On 30th day of incubation, soil pH was significantly higher in treatment T_1 (4.79) followed by T_7 (4.72), T_4 (4.71) and T_9 (4.69), which were found to be significantly different. The lowest pH was observed in T_{12} (4.31) which was on par with T_{10} (4.34). On 45th day of incubation, T_1 recorded the highest pH (4.85), which was statistically on par with T_4 (4.82). The lowest pH was recorded by T_{12} (4.37). On 60th day of incubation, T_1 recorded the highest pH (4.96), which was on par with T_4 (4.93) and T_9 (4.93). The lowest pH was observed in T_{12} (4.40). On 90th day of incubation also, T_1 recorded the highest pH (5.30), followed by T_4 (5.20) and T_9 (5.16) which were found to be significantly different. The treatments T_7 (5.12), T_6(5.12) and T_2(5.11) were found to be on par. T_{12} recorded the lowest pH (4.41).

3.2 Soil pH ($CaCl_2$)

A significant variation in soil pH ($CaCl_2$) was observed across all sampling intervals due to the application of lime formulations, compared to the absolute control (Table 2). The soil pH ranged from 4.06 to 4.36, 4.12 to 4.42, 4.32 to 4.62, 4.08

to 4.80 on 15th, 30th, 45th, 60th and 90th day of incubation respectively. The pH ($CaCl_2$) of the soil showed a gradual increase from 15 to 90 days of incubation in all treatments. At each sampling interval, the lowest pH was consistently recorded under absolute control whereas the highest pH was observed under T_1 (BL + FA + SM).

On 15th day of incubation, treatment T_1 exhibited the highest soil pH (4.36) which was significantly higher than all other treatments. The lowest pH was observed in T_{12} (4.06). On 30th day of incubation, T_1 recorded the highest pH (4.85), which was statistically on par with T_4 (4.82). The lowest pH again was recorded by T_{12} (4.37). At 30 days of incubation, the highest soil pH was observed in T_1 (4.42), followed by T_4 (4.39), T_9 (4.32) and T_7 (4.30) with no significant variation among these treatments. The lowest pH was recorded in T_{12} (4.12). At 45 days, treatment T_1 exhibited the highest pH value (4.62), which was significantly higher than T_4 (4.56), T_7 (4.53) and T_9 (4.52). The lowest pH values were observed in T_{10} (4.32) and T_{12} (4.32), which were found to be on par. At 60 days of incubation, T_1 recorded the highest pH (4.80), which was significantly higher than all other treatments. The lowest pH was observed in T_{12} (4.08). On 90th day of incubation, T_1 recorded the highest pH (4.97) which was found to be on par T_9 (4.91), T_7 (4.91) and T_4 (4.86). The lowest pH ($CaCl_2$) value was observed in T_{12} (3.98).

Table 1. Effect of treatments on soil pH (water) during incubation

Treatment	Days of incubation				
	15	**30**	**45**	**60**	**90**
T_1 (BL + FA + SM)	4.71^{a}	4.79^{a}	4.85^{a}	4.95^{a}	5.30^{a}
T_2 (BL + PMA + SM)	4.63^{bc}	4.64^{c}	4.67^{d}	4.86^{de}	5.11^{d}
T_3 (BL + PFA + SM)	4.45^{d}	4.58^{d}	4.74^{c}	4.82^{f}	4.96^{g}
T_4 ($CaCO_3$ + FA + SM)	4.66^{ab}	4.71^{b}	4.82^{ab}	4.93^{ab}	5.20^{b}
T_5 ($CaCO_3$ + PMA + SM)	4.60^{bc}	4.62^{c}	4.75^{c}	4.68^{g}	4.81^{h}
T_6 ($CaCO_3$ + PFA + SM)	4.49^{d}	4.52^{e}	4.57^{e}	4.89^{cd}	5.12^{d}
T_7 ($CaCO_3$ + PG + FA + SM)	4.65^{abc}	4.72^{b}	4.81^{b}	4.91^{bc}	5.00^{f}
T_8 ($CaCO_3$ + PG + PMA + SM)	4.59^{c}	4.63^{c}	4.63^{d}	4.85^{e}	5.12^{d}
T_9 (Dolomite + FA + SM)	4.64^{abc}	4.69^{b}	4.81^{b}	4.93^{ab}	5.16^{c}
T_{10} (Dolomite + PMA + SM)	4.47^{d}	4.34^{f}	4.42^{f}	4.43^{h}	4.62^{i}
T_{11} ($CaCO_3$ alone)	4.51^{d}	4.55^{e}	4.65^{d}	4.70^{g}	5.06^{e}
T_{12} (Absolute control)	4.31^{e}	4.31^{f}	4.37^{g}	4.40^{i}	4.41^{j}
SE ± (m)	0.023	0.011	0.012	0.009	0.011
CD (0.05)	0.072	0.034	0.037	0.028	0.034

Table 2. Effect of treatments on soil pH ($CaCl_2$) during incubation

Treatment	Days of incubation				
	15	**30**	**45**	**60**	**90**
T_1 (BL + FA + SM)	4.36^{a}	4.42^{a}	4.62^{a}	4.80^{a}	4.97^{a}
T_2 (BL + PMA + SM)	4.20^{hi}	4.26^{f}	4.36^{gh}	4.36^{i}	4.82^{c}
T_3 (BL + PFA + SM)	4.25^{cde}	4.28^{e}	4.49^{cd}	4.66^{e}	4.62^{e}
T_4 ($CaCO_3$ + FA + SM)	4.32^{b}	4.39^{b}	4.56^{b}	4.78^{bc}	4.86^{bc}
T_5 ($CaCO_3$ + PMA + SM)	4.21^{gh}	4.22^{h}	4.50^{c}	4.70^{d}	4.81^{c}
T_6 ($CaCO_3$ + PFA + SM)	4.18^{i}	4.19^{i}	4.40^{fg}	4.54^{g}	4.69^{d}
T_7 ($CaCO_3$ + PG + FA + SM)	4.26^{cd}	4.30^{d}	4.53^{bc}	4.72^{b}	4.91^{b}
T_8 ($CaCO_3$ + PG + PMA + SM)	4.23^{efg}	4.24^{g}	4.41^{ef}	4.65^{e}	4.85^{c}
T_9 (Dolomite + FA + SM)	4.27^{c}	4.32^{c}	4.52^{bc}	4.72^{b}	4.91^{b}
T_{10} (Dolomite + PMA + SM)	4.22^{fgh}	4.22^{h}	4.32^{h}	4.39^{h}	4.48^{f}
T_{11} ($CaCO_3$ alone)	4.24^{def}	4.21^{h}	4.45^{de}	4.58^{f}	4.69^{d}
T_{12} (Absolute control)	4.06^{j}	4.12^{j}	4.32^{h}	4.08^{j}	3.98^{g}
SE ± (m)	0.009	0.006	0.017	0.007	0.019
CD (0.05)	0.026	0.017	0.049	0.019	0.054

3.3 Exchangeable Acidity

On 15th day of incubation, treatment T_1 exhibited the lowest exchangeable acidity (2.23 meq 100g^{-1}), which was found to be on par with T_4 (2.28 meq 100g^{-1}) and T_7 (2.29 meq 100g^{-1}). T_7 was found to be on par with T_9 (2.30 meq 100g^{-1}). The highest value was observed in absolute control T_{12} (2.69 meq 100g^{-1}), which was on par with T_{10} (2.65 meq 100g^{-1}). On 30th day, T_1 showed the lowest value (2.17 meq 100g^{-1}) which was on par with T_7 (2.21 meq 100g^{-1}), T_9 (2.22 meq 100g^{-1}), T_4 (2.24 meq 100g^{-1}) and T_5 (2.26 meq 100g^{-1}). The highest exchangeable acidity was observed in absolute control T_{12} (2.57 meq 100g^{-1}) which was statistically on par with T_{10} (2.46 meq 100g^{-1}), T_3 (2.45 meq 100g^{-1}) and T_6 (2.43 meq 100g^{-1}). On 45th day of incubation, T_1 recorded the minimum acidity (2.04 meq 100g^{-1}), which was on par with T_4 (2.05 meq 100g^{-1}). The treatment T_7 (2.12 meq 100g^{-1}) and T_9 (2.17 meq 100g^{-1}) were found to be on par and T_{12} showed the highest value (2.68 meq 100g^{-1}). On 60th day, the lowest exchangeable acidity was found in T_1 and T_7 (1.98 meq 100g^{-1}) which was on par with T_4 (2.00 meq 100g^{-1}) and T_9 (2.01 meq 100g^{-1}). T_{12} again showed the highest acidity (2.61 meq 100g^{-1}). On 90th day, T_1 registered the lowest acidity (1.80 meq 100g^{-1}), followed by T_7 (1.85 meq 100g^{-1}), T_4 (1.86 meq 100g^{-1}) and T_9 (1.88 meq 100g^{-1}), which were found to be on par and lowest value of 2.56 meq 100g^{-1} registered in T_{12} (Table 3). The applied lime formulations exhibited a progressive decrease in exchangeable acidity from 15th to 90th days of incubation. In treatment T_1, it decreased from 2.23 meq 100g^{-1} (15th day) to 1.80 (90th day) during incubation.

3.4 Exchangeable H^+

The lowest exchangeable H^+ at 15 days of incubation was observed in T_1 (0.62 meq 100g^{-1}) which was followed by T_4 (0.64 meq 100g^{-1}) and T_9 (0.67 meq 100g^{-1}), which differ significantly. The highest exchangeable H^+ was recorded in T_{12} (0.78 meq 100g^{-1}), which was significantly higher than all other treatments. However, T_{10} (0.76 meq 100g^{-1}) and T_3 (0.75 meq 100g^{-1}) were statistically on par. At 30 days of incubation, treatment T_1 exhibited the lowest exchangeable H^+ value (0.57 meq 100g^{-1}), followed by T_4 (0.52 meq 100g^{-1}), which were statistically on par. T_{12} exhibited the highest exchangeable H^+ of 0.75 meq 100 g^{-1}. On 45th day of incubation, the lowest exchangeable H^+ was recorded in T_9 (0.52 meq 100g^{-1}), followed by T_1 (0.53 meq 100g^{-1}) and T_4 (0.55 meq 100g^{-1}). T_9 and T_1 were statistically on par. The highest value was observed in T_{12} (0.79 meq 100g^{-1}). Similarly, at 60th day of incubation, T_9 (0.48 meq 100g^{-1}) registered the lowest exchangeable H^+ content which was statistically on par with T_1 (0.49 meq 100g^{-1}). The highest exchangeable H^+ was observed by T_{12} (0.73 meq 100g^{-1}). At 90 days of incubation, T_1 recorded the lowest exchangeable H^+ (0.29 meq 100g^{-1}), followed by T_9 (0.40 meq 100g^{-1}) and T_4 (0.40 meq 100g^{-1}) and were found to be on par with T_1. The highest value was observed by T_{12} (0.71 meq 100g^{-1}) which was found to be on par with T_3 (0.61 meq 100g^{-1}) and T_6 (0.58 meq 100g^{-1}). The results clearly indicated that exchangeable H^+ content declined during the incubation period from 15 to 90 days irrespective of treatments. It decreased from 0.78 meq 100 g^{-1} in control (T_{12} on 15th day) to 0.29 meq 100 g^{-1} in treatment T_1 applied with BL+FA+SM during incubation (Table 4).

3.5 Exchangeable Al^{3+}

The exchangeable Al in soil ranged between 1.61 to 1.91 meq 100g^{-1}, 1.52 to 1.94 meq 100 g^{-1}, 1.49 to 1.89 meq 100 g^{-1}, 1.16 to 1.86meq 100 g^{-1}, 1.35 to 1.85 meq 100g^{-1} on 15th, 30th, 45th, 60th and 90th days of incubation respectively. On 15th day of incubation, the lowest concentration of exchangeable Al was recorded under treatment T_4 (1.61 meq 100g^{-1}), which were found to be on par with T_1 (1.62 meq 100g^{-1}), followed by T_7 (1.64 meq 100g^{-1}) and T_9 (1.65 meq 100g^{-1}) were found to be on par. The highest exchangeable Al content was observed in T_{12} (1.91 meq 100g^{-1}), which was statistically on par with T_8 (1.90 meq 100g^{-1}). On 30th day of incubation, treatment T_1 (1.52 meq 100g^{-1}) exhibited the lowest exchangeable Al content, which was significantly different from other treatments. The treatment T_9 (1.68 meq 100g^{-1}), T_5 (1.69) and T_6 (1.69) were found to be on par. The maximum exchangeable Al was found in T_{12} (1.94 meq 100g^{-1}). At 45 days of incubation, the lowest exchangeable acidity was noted under T_1 (1.49 meq 100g^{-1}), followed by T_4 (1.51 meq 100g^{-1}), T_9 (1.51 meq 100g^{-1}) and T_7 (1.52 meq 100g^{-1}). The highest value was observed in T_{12} (1.89 meq 100g^{-1}), which was significantly higher than all other treatments. At 60 days of incubation, the lowest exchangeable acidity was recorded under T_1 (1.16 meq 100g^{-1}), followed by T_4 (1.42 meq 100g^{-1}), however both were on par. The highest value was recorded in T_{12} (1.86 meq 100g^{-1}). At 90 days of incubation, T_1 (1.35 meq 100g^{-1}) exhibited the lowest value of exchangeable acidity, which was significantly lower than all other treatments was followed by T_4 (1.38 meq $100g^{-1}$) and T_7 (1.40 meq $100g^{-1}$), which were statistically on par. The highest value was recorded under T_{12} (1.85 meq $100g^{-1}$), significantly exceeding all other treatments which was followed by T_5 (1.62 meq $100g^{-1}$) and T_{10} (1.62 meq $100g^{-1}$), which were found to be on par (Table 5).

Table 3. Effect of treatments on exchangeable acidity during of incubation, meq $100g^{-1}$

Treatment	Days of incubation				
	15	30	45	60	90
T_1 (BL + FA + SM)	2.23^{h}	2.17^{e}	2.04^{g}	1.98^{gh}	1.80^{f}
T_2 (BL + PMA + SM)	2.44^{de}	2.33^{bcd}	2.21^{de}	2.13^{de}	2.00^{cd}
T_3 (BL + PFA + SM)	2.53^{c}	2.45^{abc}	2.24^{d}	2.24^{bc}	2.12^{b}
T_4 ($CaCO_3$ + FA + SM)	2.28^{h}	2.24^{de}	2.05^{g}	2.00^{gh}	1.85^{ef}
T_5 ($CaCO_3$ + PMA + SM)	2.37^{ef}	2.26^{de}	2.35^{b}	2.10^{def}	1.90^{def}
T_6 ($CaCO_3$ + PFA + SM)	2.42^{def}	2.43^{abc}	2.26^{cd}	2.18^{cd}	2.11^{b}
T_7 ($CaCO_3$ + PG + FA + SM)	2.29^{gh}	2.21^{de}	2.12^{f}	1.98^{h}	1.85^{ef}
T_8 ($CaCO_3$ + PG + PMA + SM)	2.61^{b}	2.31^{cd}	2.20^{de}	2.32^{b}	2.08^{bc}
T_9 (Dolomite + FA + SM)	2.35^{fg}	2.22^{de}	2.17^{ef}	2.01^{fgh}	1.88^{ef}
T_{10} (Dolomite + PMA + SM)	2.65^{ab}	2.46^{ab}	2.31^{bc}	2.13^{de}	2.09^{bc}
T_{11} (CaCO3 alone)	2.48^{cd}	2.32^{bcd}	2.21^{de}	2.07^{efg}	1.95^{de}
T_{12} (Absolute control)	2.69^{a}	2.57^{a}	2.68^{a}	2.61^{a}	2.56^{a}
SE ± (m)	0.024	0.049	0.022	0.032	0.034
CD (0.05)	0.071	0.142	0.063	0.092	0.101

Table 4. Effect of treatments on exchangeable H^+ during incubation, meq $100g^{-1}$

Treatment	Days of incubation				
	15	30	45	60	90
T_1 (BL + FA + SM)	0.62^{h}	0.51^{de}	0.53^{g}	0.49^{hi}	0.29^{d}
T_2 (BL + PMA + SM)	0.72^{d}	0.67^{abc}	0.65^{b}	0.60^{c}	0.53^{bc}
T_3 (BL + PFA + SM)	0.75^{bc}	0.70^{ab}	0.64^{b}	0.66^{b}	0.61^{ab}
T_4 ($CaCO_3$ + FA + SM)	0.64^{g}	0.52^{de}	0.61^{c}	0.51^{fg}	0.40^{cd}
T_5 ($CaCO_3$ + PMA + SM)	0.69^{e}	0.57^{bcd}	0.55^{f}	0.51^{fg}	0.43^{c}
T_6 ($CaCO_3$ + PFA + SM)	0.72^{d}	0.61^{abcd}	0.59^{d}	0.52^{ef}	0.58^{ab}
T_7 ($CaCO_3$ + PG + FA + SM)	0.71^{d}	0.55^{cd}	0.57^{e}	0.50^{gh}	0.43^{cd}
T_8 ($CaCO_3$ + PG + PMA + SM)	0.74^{c}	0.59^{bcd}	0.64^{b}	0.56^{d}	0.49^{bc}
T_9 (Dolomite + FA + SM)	0.67^{f}	0.57^{bcd}	0.52^{g}	0.48^{i}	0.40^{cd}
T_{10} (Dolomite + PMA + SM)	0.76^{b}	0.63^{abcd}	0.60^{cd}	0.53^{e}	0.51^{bc}
T_{11} ($CaCO_3$ alone)	0.68^{ef}	0.61^{abcd}	0.56^{ef}	0.59^{c}	0.43^{c}
T_{12} (Absolute control)	0.78^{a}	0.75^{a}	0.79^{q}	0.73^{a}	0.71^{a}
SE (m) ±	0.006	0.006	0.006	0.006	0.048
CD (0.05)	0.018	0.017	0.017	0.018	0.141

Table 5. Effect of treatments on exchangeable aluminium during incubation, meq $100g^{-1}$

Treatment	Days of incubation				
	15	30	45	60	90
T_1 (BL + FA + SM)	1.62^{i}	1.52^{i}	1.49^{j}	1.16^{d}	1.35^{i}
T_2 (BL + PMA + SM)	1.72^{f}	1.80^{c}	1.56^{h}	1.53^{bc}	1.47^{f}
T_3 (BL + PFA + SM)	1.78^{e}	1.75^{d}	1.62^{f}	1.64^{abc}	1.51^{d}
T_4 ($CaCO_3$ + FA + SM)	1.61^{i}	1.65^{g}	1.78^{b}	1.42^{cd}	1.38^{h}
T_5 ($CaCO_3$ + PMA + SM)	1.67^{g}	1.69^{f}	1.52^{i}	1.46^{bc}	1.62^{b}
T_6 ($CaCO_3$ + PFA + SM)	1.84^{c}	1.69^{f}	1.58^{g}	1.51^{bc}	1.49^{e}
T_7 ($CaCO_3$ + PG + FA + SM)	1.64^{h}	1.62^{h}	1.51^{ij}	1.49^{bc}	1.40^{h}
T_8 ($CaCO_3$ + PG + PMA + SM)	1.90^{ab}	1.82^{bc}	1.74^{c}	1.73^{ab}	1.45^{g}
T_9 (Dolomite + FA + SM)	1.65^{gh}	1.68^{f}	1.51^{ij}	1.70^{abc}	1.57^{c}
T_{10} (Dolomite + PMA + SM)	1.89^{b}	1.83^{b}	1.71^{d}	1.63^{abc}	1.62^{b}

Treatment	Days of incubation				
	15	30	45	60	90
T_{11} ($CaCO_3$ alone)	1.80^{d}	1.72^{e}	1.65^{e}	1.57^{bc}	1.52^{d}
T_{12} (Absolute control)	1.91a	1.94a	1.89a	1.86a	1.85^{a}
SE ± (m)	0.006	0.006	0.007	0.097	0.007
CD (0.05)	0.018	0.019	0.02	0.283	0.019

4. DISCUSSION

The result of the soil pH(water), pH ($CaCl_2$), exchangeable acidity, H^+ and Al^{3+} are discussed here under.

4.1 Soil pH (Water and $CaCl_2$)

The present study demonstrated a significant improvement in soil pH, measured both in water and in $CaCl_2$, across all lime treatments over the 90 days of incubation.

Among the treatments, T_1 (BL+ Fulvic Acid + Silicate Mixture) recorded the highest pH values throughout the incubation period. In T_1 pH(water) increased from 4.71 to 5.30 while pH ($CaCl_2$), values rose from 4.36 to 4.97 at 15th to 90th day of incubation. The superior effect of T_1(BL+FA+SM) due to the the synergistic action of its components like CaO which provided rapid reactivity and immediate neutralization of H^+ ions (Mahmud & Chong, 2022) further fulvic acid chelated toxic Al^{3+} ions thereby reducing acidity and enhancing soil buffering capacity (Yang *et al.,* 2013) and the silicate mixture contributed long-term buffering by releasing Si that formed stable Al-silicate complexes and by supplying additional base cations (Na^+, K^+, Ca^{2+}) (Datnoff *et al.,* 2001; Ma & Takahashi, 2002). The final pH (water) values on 90th day of incubation were 5.20(T_4), 5.16(T_9), and 5.00(T_7) respectively, while the corresponding pH ($CaCl_2$) values were 4.86(T_4), 4.91(T_7), and 4.91(T_9) which were applied with fulvic acid. The relatively high effectiveness of these treatments underscores the importance of fulvic acid in enhancing the performance of $CaCO_3$ and dolomite. These findings align with previous research, which demonstrated that lime, dolomite, and silicate amendments improve soil acidity both by neutralizing H^+ and by precipitating Al as less toxic forms (Haynes & Mokolobate, 2001, Rosilawati *et al.,*2014). Moreover, the addition of organic acids such as fulvic acid enhances the solubility of Ca and Si while simultaneously chelating toxic Al species (Yang *et al.,* 2013; Ch'ng *et al.,* 2014). Zhang *et al.* (2023) reported that soil amendments, particularly lime and organic materials, significantly increased soil pH worldwide, with the greatest improvements observed in strongly acidic soils (pH < 5.0), highlighting their effectiveness in mitigating soil acidity and improving soil chemical conditions.

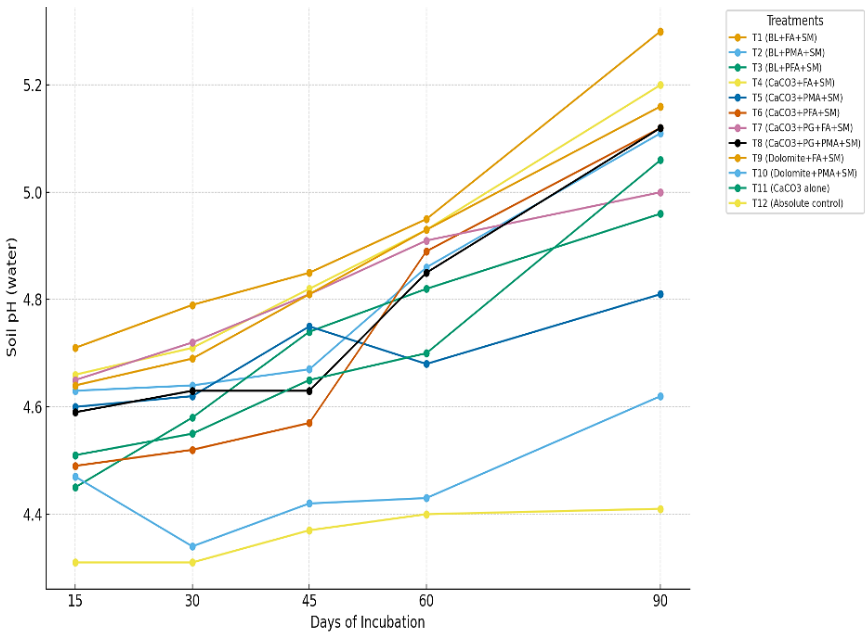

Fig.1. pH(water) as influenced by lime treatments during incubation

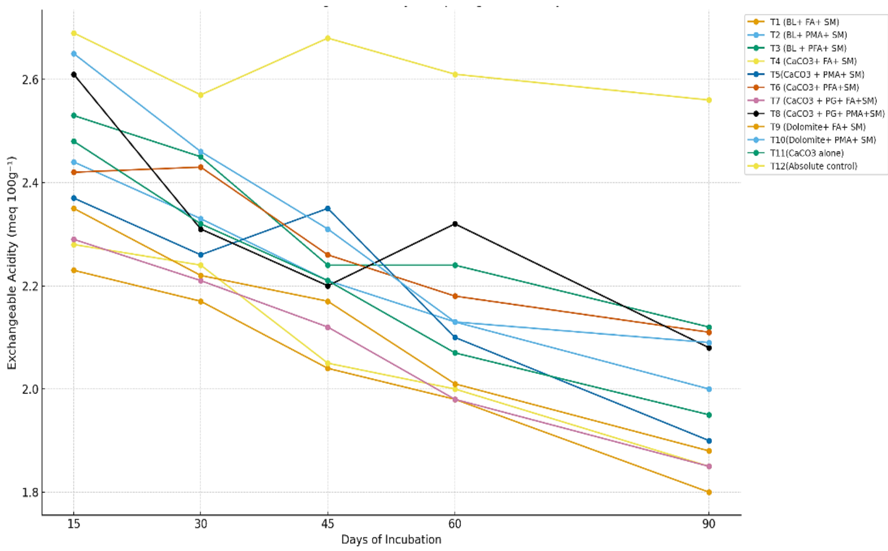

Fig. 2. Exchangeable acidity (meq $100g^{-1}$) as influenced by lime treatments

4.2 Exchangeable Acidity, Al^{3+}, and H^+

The result of incubation study revealed that the application of lime formulations, organic acids, and silicate mixtures had a pronounced effect on ameliorating soil acidity by reducing exchangeable acidity, Al^{3+}, and H^+ over the 90 days of incubation period. Among all treatments, T_1 (BL + FA + SM) consistently recorded the lowest values of exchangeable acidity, Al^{3+}, and H^+ throughout the incubation period. In T_1(BL+FA+SM), exchangeable acidity decreased from 2.23 meq $100g^{-1}$ (15^{th} day) to 1.80 meq $100g^{-1}$(90^{th} day). exchangeable Al^{3+} declined from 1.62 to 1.35 meq $100g^{-1}$ and exchangeable H^+ decreased from 0.62 to 0.29 meq $100g^{-1}$ respectively. The superior performance of this treatment is attributed to the rapid hydrolysis of burnt lime, which releases OH^- ions that neutralize soil acidity, coupled with the chelating effect of fulvic acid, which binds Al^{3+} and Fe^{2+} ions, reducing their phytotoxicity. Additionally, the inclusion of the silicate mixture (Ca-, K-, and Na-silicates) contributed to sustained amelioration by supplying base cations that participate in cation exchange reactions and by promoting the formation of stable Al-silicate complexes, which further mitigate acidity and Al^{3+} activity in the soil solution (Ning *et al.,* 2016; Azman *et al.,* 2023). The absolute control (T_{12}) treatment exhibited the highest exchangeable acidity, Al^{3+} and H^+ throughout the incubation. This reflects the strong inherent acidity of the experimental soil, compounded by ongoing oxidation of sulphidic minerals, which continuously released protons and Al^{3+} into the soil solution (Dent & Pons, 1995).

5. CONCLUSION

The findings confirm that integrating lime, fulvic acid, and silicate mixtures is the most effective approach for ameliorating acid sulphate soils by simultaneously neutralizing H^+, reducing Al^{3+} activity through precipitation and complexation, and lowering overall exchangeable acidity. These results align with earlier studies highlighting the importance of combining chemical and organic amendments to improve soil chemical properties and reduce proton and aluminum toxicity in acidic soils (Ch'ng *et al.,* 2014; Rosilawati *et al*., 2014).

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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