

Review Article

Review: The Role of Reclaiming Materials in Soil Acidity and Soil Chemical Properties in Western Ethiopia

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Abstract

Soil acidity is a major challenge for soil production in the Ethiopian highlands. This review aims to address the causes, extent, and management practices of soil acidity. Acidic soils hinder agricultural activities in the region and are on the rise. To combat this issue and improve crop yields, farmers can use simple and sustainable methods like liming. Liming is crucial for raising soil pH and boosting crop productivity. In Ethiopia, the gap between potential and actual yields is significant due to soil acidity and toxic nutrient availability. Applying mineral fertilizers without addressing soil acidity is ineffective. Effective acid soil management practices are essential for improving yield production. This review focuses on the role of liming in soil chemical properties, causes and management of soil acidity, and its impact on soil fertility and crop yield. Integrated acid soil management enhances yield sustainability and maximizes nutrient use efficiency.

Keywords

Acidity, Fertility, Depletion, Reclamation

1. Introduction

Soil acidity, coupled with limited nutrient availability, is a major constraint that can lead to reduced productivity in acid soils. While acidification is a natural process, human activities such as agriculture and pollution can accelerate this phenomenon [29]. In many highland regions of Ethiopia, soil acidity poses a significant challenge that must be addressed promptly due to its negative impact on crop yield and output. Soil acidity is associated with the toxicity of Al, H, Fe, and Mn to plant roots in the soil solution, resulting in deficiencies of available nutrients such as P, Mo, Ca, Mg, and K [15].

The productivity of agricultural systems on acidic soil can be enhanced through the application of lime. The lime amendment increases nutrient availability and improves soil fertility, unless constrained by low soil pH [5]. Liming raises

soil pH and enhances microbial activity, leading to improved decomposition of soil organic matter, which in turn increases mineral N, P, and loss of soil organic carbon through carbon dioxide emissions [6]. In strongly acidic soils, liming promotes high rates of nitrification [7]. This increase in nitrification is attributed to elevated microbial activity following lime application, which raises soil pH. Changes in microbial responses may also be influenced by variations in soil lime requirements and organic matter content [26]. The mineralization process and microbial community responses to liming vary depending on management practices and soil type, with increased protection of organic substrates leading to enhanced stability [9].

Liming raises soil pH by introducing calcium and magne-

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sium, leading to the precipitation of aluminum and manganese in the soil solution. In highly acidic soils, liming not only enhances microbial activity but also improves phosphorus availability by reducing aluminum and iron ions and their fixation on aluminum and iron oxides [16]. Excessive liming can result in the precipitation of calcium phosphate when pH values exceed 8.5 [16]. In humid tropical regions with high precipitation, soils naturally become acidic due to the leaching of basic cations. When soil pH drops below 5, aluminum becomes highly soluble in water and dominates the soil solution [19]. To address soil acidity and enhance productivity in strongly acidic soils, various practices are recommended, including cultivating acid-tolerant plants, covering the surface with non-acidic soil, using organic fertilizers, and applying lime. Among these practices, liming and organic fertilizer application are considered the most effective measures due to their long-lasting effects. This review aims to explore the impact of liming on soil acidity, soil chemical properties, and identify management practices for mitigating the effects on soil fertility.

2. Role of Lime in Soil Acidity and Soil Chemical Properties in Ethiopia

2.1. Soil Acidity Levels

Soil quality is essential for sustainable soil functions. Soil acidity is a major global issue leading to land degradation, affecting approximately 30% of ice-free soils, totaling close to 4 billion hectares. The need to increase agricultural production puts pressure on fragile soils, leading to toxic levels of aluminum and manganese, compaction, and erosion. Regions with tropical, subtropical, and moderate climates are particularly affected by soil acidity, with 32% of arable land globally being acidic. Ultisols, Entisols, and Oxisols account for two-thirds of acidic soils worldwide [20]. Soil acidity is a significant challenge for land degradation, impacting thirty percent of ice-free soils globally [25].

2.2. Major Acid Soils in Ethiopia

The primary soil classes affected by soil acidity in Ethiopia are Nitisols and Oxisols. In acidic soil conditions, there is a continuous decrease in soil cations like Ca, Mg, and K. Soil acidity is established at a $\text{pH} < 5.5$ due to deficiencies in nitrogen, phosphorus, sulfur, and other nutrients, along with high levels of manganese and aluminum, which hinder crop growth. The predominant soil associations are Orthic Acrisols and Dystric Nitisols, with some Dystric Cambisols and Lithosols on steep slopes. Eutric Nitisol is the main soil type in the central highlands of Ethiopia, where soil acidity is a concern. In the western part of Ethiopia, Nitisols are common and contain inorganic materials like metamorphic, volcanic, felsic materials, limestone, granite, and sandstones.

Poor farm management practices, intensive cultivation, and topographical factors contribute to acidity issues in these soil types [32].

2.3. Causes of Soil Acidity

Soil acidification is the process of soil becoming more acidic due to human activities and natural processes that lower the soil pH. Inefficient use of nitrogen, especially with ammonium-based fertilizers, is a significant factor in soil acidification. Ammonium nitrogen in fertilizers easily converts to nitrate and hydrogen ions in the soil, worsening soil acidity. Various factors, such as acidic parent material, fertilizer application, organic matter decomposition, climate, cation removal through crop harvest, land use changes, and soil buffer capacity, all contribute to soil acidity [1].

2.3.1. Climate Influences

Soil formation is influenced by factors such as precipitation, humidity, temperature, and cloud cover. In arid climates, plants accumulate calcium, magnesium, potassium, sodium, and chlorine, while humid tropical conditions lead to silicon, iron, aluminum, and minimal basic element accumulation due to leaching. Dry regions have high base content from water percolation, while high rainfall areas experience reduced dissolved salts, causing gypsum and calcium carbonate detachment. Wet climates can lead to acidic soil development due to extreme rainfall washing away essential basic elements, resulting in leaching of magnesium and calcium and their replacement by aluminum and iron over time [18].

2.3.2. Acidic Parent Material

Rocks rich in quartz or silica, like rhyolite and granite, are classified as acid rocks due to their association with basic materials. In contrast, rocks lacking bases contribute to the formation of acidic soil materials. Soils derived from limestone are less acidic compared to those from weathered granite. Soil acidity is influenced by crop removal and leaching losses of bases. Sandy soils have higher inherent fertility from basic inorganic materials than those from sandstones. Soil pH typically falls between 4.5 to 6.5. High-altitude soils in the country are characterized by low exchangeable cations, acidity, and low base saturation [14].

2.3.3. Application of Ammonium Fertilizers

Excessive use of inorganic fertilizers without soil amendment and testing can exacerbate soil acidity. The use of nitrogen fertilizers in the form of ammonia, such as NH_4 and $\text{CO}(\text{NH}_2)_2$, as well as amino acids in organic fertilizers, can contribute to acidification [30]. The conversion of these nitrogen sources into nitrate releases hydrogen ions, which in turn lowers soil pH. Application of fertilizers containing NH_4 or the accumulation of high levels of organic matter in the soil can ultimately raise soil acidity and reduce pH levels [31].

2.3.4. Decomposition of Organic Matter

Hydrogen ions are generated through the breakdown of organic matter, leading to soil acidity. The elevated levels of carbonic acid produced by microbes and higher plants contribute to soil acidity [1]. Soil organic matter contains reactive enolic, phenolic, and carboxylic groups that function as weak acids. When these acids dissociate, they release hydrogen ions and carbon dioxide, resulting in the formation of organic acids [20].

2.3.5. Removal of Major Cations Through Crop Harvest

The cultivation of high-yield crops on small farms leads to the depletion of base cations from the soil, resulting in increased soil acidity [17]. Soil acidity is exacerbated when soils are mechanically worked and crops are grown, disrupting the balance and causing the removal of base cations through crop harvesting and leaching due to soil disturbance [23]. Essential elements like potassium (K), magnesium (Mg), and calcium (Ca) are absorbed by crops to support their growth, leading to the depletion of these lime-like nutrients in the soil as crop yields increase. High-yield crops such as alfalfa and Bermuda grass have a more significant impact on soil acidity compared to grain crops [20].

2.3.6. Land Use or Land Cover Change

Previous research suggests that converting native forest and rangeland to cultivated land leads to soil degradation, including increased soil acidity, reduced cation exchange capacity (CEC), and soil organic matter (SOM) content, resulting in decreased soil fertility (Lemenih, 2004). Land use practices such as overgrazing, deforestation, mineral fertilization, and continuous cultivation have been shown to significantly impact soil properties and reduce productivity. Land use systems also influence exchangeable aluminum, effective cation exchange capacity, available phosphorus, organic carbon, exchangeable cations, soil pH, total nitrogen, and aluminum [10].

2.3.7. Low Buffer Capacity of the Soil

The study [2] states that the lime requirement of acidic soils is influenced by their buffer capacity, which is determined by the levels of organic matter and clay. Soils with higher buffer potential, containing more clay and organic matter, will need more lime if they are acidic. On the other hand, soils with low buffer capacity, like sandy soils with minimal organic matter, will have lower lime requirements even if they are acidic [2].

2.4. Effect of Soil Acidity on Nutrient Availability

Soil acidity and low nutrient availability are significant constraints to crop production on acid soils [1]. The availa-

bility and solubility of essential nutrients for plants are closely linked to soil pH, affecting nutrient uptake. Excessive soluble Al, Mn, and other metallic ions, along with insufficient Ca, P, and Mo, contribute to soil acidity [28].

When the soil pH drops below 5.5, phosphate becomes less available to plant roots. Crops require a certain amount of phosphorus in the soil solution for optimal growth, ranging from 0.13 to 1.31 kg per hectare, as they absorb around 0.44 kg per hectare per day. The labile fraction of phosphorus in the topsoil ranges from 65 to 218 kg per hectare, which can potentially replace soil solution phosphorus [4].

Soil acidity, particularly at pH 5.5 or lower, can hinder the growth of sensitive plant species, while having minimal impact on insensitive species, even at pH levels below 4. This pH effect is often exacerbated by aluminum and manganese toxicity, as well as calcium and molybdenum deficiencies [13].

2.5. Aluminum and Manganese Toxicity

Soil acidity is commonly assessed using the pH scale, which measures the concentration of protons (H^+) in a solution. N^{2-} fixing legumes release H^+ in the root zone, leading to increased acidity in acid soils with pH levels dropping below 4. Aluminum (Al) toxicity is a significant issue in acid soils, where phytotoxic forms of Al, such as Al^{3+} and $Al(OH)^{2+}$, are released into the soil solution. Most plant species are sensitive to Al, which limits plant productivity in acidic soils by affecting root growth and disrupting plant metabolism. Manganese (Mn) is an essential nutrient for plants, easily transported from roots to shoots. Excessive Mn levels in soils can cause toxicity symptoms in shoots and hinder the uptake of other essential nutrients like calcium (Ca^{2+}) and magnesium (Mg^{2+}).

2.6. Soil Acidity Management

Managing acid soil involves adjusting soil acidity through amendments and implementing agricultural practices to optimize yields. Soil pH is crucial for nutrient availability and toxicity reduction [8]. For example, low pH can lead to aluminum toxicity, phosphorus unavailability, and calcium depletion. Conversely, raising pH can render iron and other micronutrients unavailable, as they become insoluble [27].

Liming

Liming is a soil treatment method that involves adding magnesium- and calcium-rich substances such as hydrated lime, marl, chalk, or limestone [11]. This practice is essential for neutralizing soil acidity and improving nutrient availability. However, excessive liming can lead to micronutrient deficiencies, particularly iron. Soil acidity can hinder plant growth by affecting root development, water uptake, and nutrient absorption. The benefits of liming include enhanced phosphorus availability, increased pH levels, improved root growth, and nutrient uptake. Calcitic or dolomitic limestone is a cost-effective option for liming. Studies have shown that

applying lime at specific rates can reduce aluminum content and increase soil pH, leading to improved soil conditions.

2.7. Effect of Liming on Soil Chemical Properties

2.7.1. Soil pH

According to Moody and Cong (2008), soil pH significantly increased with higher levels of lime application ($P \leq 0.05$) (Figure 1). The highest soil pH recorded was 6.15 with the application of 24373 mg of lime per kg of soil, followed by 18280 mg of lime per kg of soil (Figure 1). Applying the highest lime rate of 24373 mg/kg increased soil pH by 1.48 units compared to the control [3]. Even with half the amount of lime needed to neutralize the soil (6093 mg/kg of soil), an increase in soil pH was observed compared to the control. Similar results were reported in Ethiopia, where the application of 3 tons of lime per hectare raised the pH from 4.8 to 6.3 after barley harvest, and the application of 2.2 tons per hectare increased the pH from 4.8 to 5. The increase in pH

after lime application is attributed to the removal of hydrogen by calcium from lime (CaCO_3), leading to a rise in pH [12].

2.7.2. Exchangeable Acidity (H^+ and Al^{3+})

According to Oluwatoyinbo, soil exchangeable acidity decreased significantly with increasing rates of lime and phosphorus, as well as their interaction effects. The application of the maximum lime rate (24373 mg/kg soil) combined with the maximum P fertilizer (1600 mg/kg soil) significantly reduced soil exchangeable acidity to $0.027 \text{ cmol (+) kg}^{-1}$ compared to the control pots with the highest mean exchangeable acidity of $2.174 \text{ cmol (+) kg}^{-1}$. The decrease in exchangeable acidity with liming is attributed to the replacement of aluminum by calcium in the exchange site and subsequent precipitation of aluminum as Al(OH)_3 . Phosphorus additions as $\text{Ca(H}_2\text{PO}_4)_2$ also increased the exchangeable calcium content of the soil, leading to the formation of insoluble Al(OH)_3 at high pH, similar to the lime and phosphorus interaction effects on exchangeable acidity.

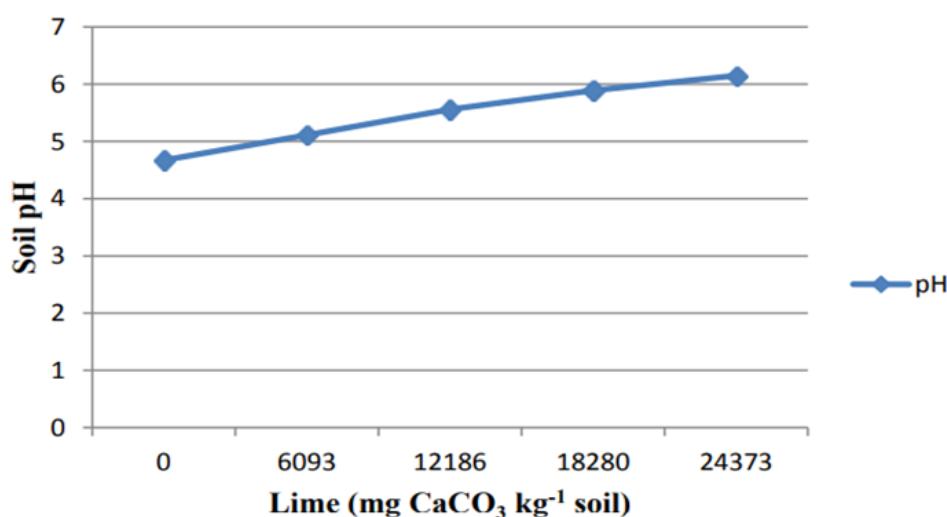


Figure 1. Effect of lime on pH values of acid soils after harvest.

The variable follows a linear order model (Figure 1) with high statistical significance (Table 1), indicating that the decrease in exchangeable acidity is influenced by the type of liming material used. The results show significant differ-

ences among treatments, with the control treatment (0 t ha^{-1}) being statistically distinct from the other treatments. This suggests that the application of the amendment doses effectively reduces exchangeable acidity.

Table 1. Physicochemical characteristics of the soil.

pH	Mo	P	Ca	Mg	Na	K	Al
	%	mg/kg	cmol+/kg	cmol+/kg	cmol+/kg	cmol+/kg	
4.3	0.3	4.8	2.3	0.9	0.5	0.03	8.8

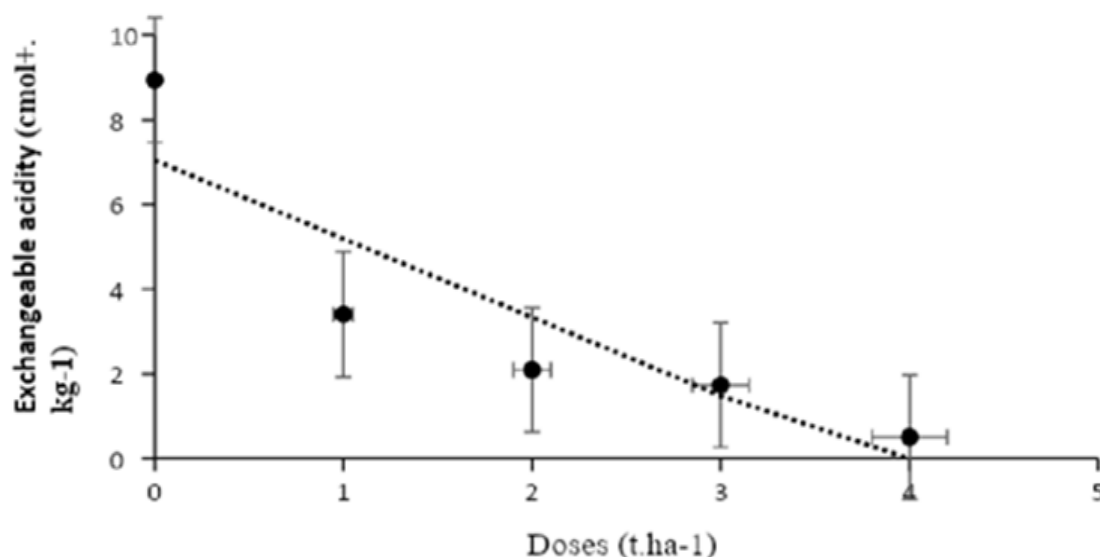


Figure 2. Effect of lime and phosphorus on soil exchangeable acidity (cmol kg⁻¹) after harvest.

Table 2. Effect of lime on exchangeable acidity.

Treatment (mg kg ⁻¹ soil)	phosphorus					Lime mean	
	0	300	600	900	1600		
Lime	0	2.174 ^a	2.333 ^a	1.217 ^b	1.355 ^b	1.339 ^b	1.883
	6093	0.485 ^{cd}	0.273 ^{de}	0.210 ^{de}	0.160 ^{de}	0.340 ^c	0.294
	12186	0.277 ^{de}	0.123 ^e	0.080 ^e	0.110 ^e	0.093 ^e	0.127
	18280	0.060 ^e	0.043 ^e	0.073 ^e	0.040 ^e	0.080 ^e	0.059
	24373	0.047 ^e	0.030 ^e	0.043 ^e	0.037 ^e	0.027 ^e	0.037
P mean		0.598	0.561	0.325	0.340	0.376	-
LSD (0.05)				0.046			
CV (%)				13.54			

CV (%): Coefficient of Variation, LSD: Least Significant Difference

Main effect means that within a column, values followed by the same letter(s) are not significantly different at $P \leq 0.05$.

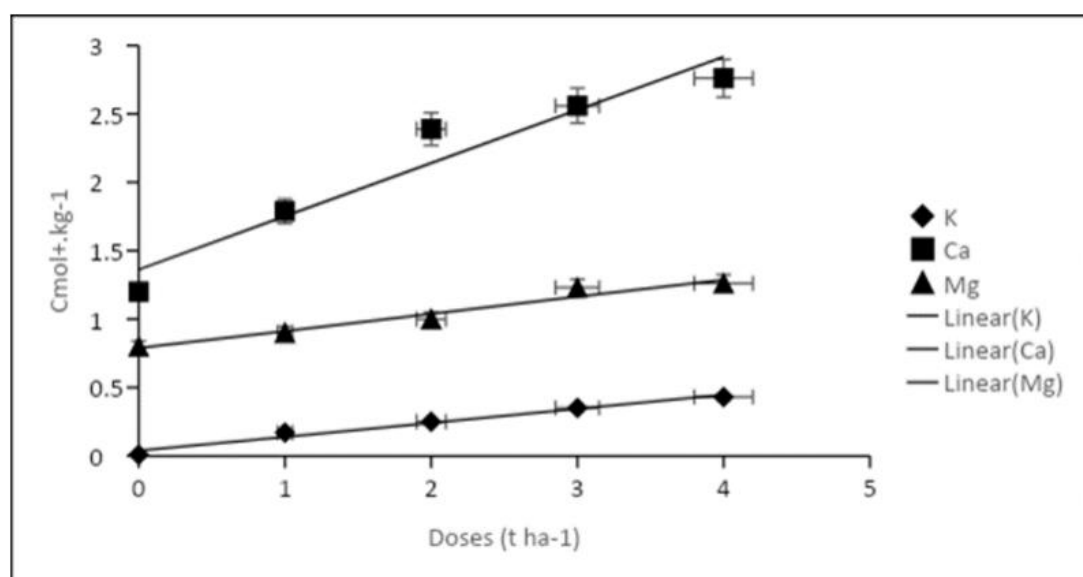
Source: Sosen Amsalu and Sheleme Beyene, 2020.

Reference: Eliecer Miguel Cabrales et al., 2020.

2.7.3. Effect of Lime on the Availability of Calcium, Magnesium, and Potassium

Liming significantly increased calcium and magnesium levels, as shown in Figure 3, consistent with previous studies [22]. There was also a slight increase in potassium, albeit to a lesser extent [24]. Reported similar results in an inceptisol

soil, where lime application increased calcium and magnesium availability without significantly affecting potassium levels. This may be due to the ability of magnesium and calcium, to a lesser extent, to replace potassium in the soil exchange complex. The data for calcium, magnesium, and potassium exhibited a linear trend, as illustrated in Figure 3, with high statistical significance ($p < 0.001$).



Source: Miguel Cabrales Herrera, Luis Fernando Acosta, 2020.

Figure 3. Effect of liming on the content of potassium, calcium, and magnesium in the soil.

2.7.4. Exchangeable Aluminum

The soil's exchangeable aluminum content decreased significantly with higher rates of lime and phosphorus application, as well as due to the interaction between lime and phosphorus (Table 3). When the full lime dose required to neu-

tralize the soil (12186 mg/kg soil) was combined with the highest phosphorus fertilizer rate (1600 mg P kg⁻¹ soil), the soil's exchangeable aluminum was almost completely reduced to zero [21].

Table 3. The impact of lime and phosphorus on the exchangeable aluminum levels (cmol kg⁻¹) in the soils after harvest.

Treatment (mg kg ⁻¹ soil)		phosphorus					Lime mean
		0	300	600	900	1600	
Lime	0	1.688 ^a	1.373 ^b	1.227 ^c	1.179 ^c	1.060 ^d	1.305
	6093	0.050 ^e	0.043 ^e	0.040 ^e	0.037 ^e	0.023 ^e	0.039
	12186	0.020 ^e	0.020 ^e	0.020 ^e	0.023 ^e	0.007 ^e	0.018
	18280	0.000 ^e	0.000 ^e	0.000 ^e	0.000 ^e	0.000 ^e	0.000
	24373	0.000 ^e	0.000 ^e	0.000 ^e	0.000 ^e	0.000 ^e	0.000
P mean		0.350	0.352	0.287	0.257	0.248	0.218
LSD (0.05)				0.023			
CV (%)				7.70			

Considering the interaction effect of lime and P, the highest mean exchangeable Al (1.688 cmol (+) kg⁻¹) was observed in the control treatments, while the lowest (0 cmol (+) kg⁻¹) was observed with the addition of 18280 and 24373 mg CaCO₃ kg⁻¹ soil, regardless of P application. This can be explained by the increased replacement of Al by Ca in the ex-

change site and the subsequent precipitation of Al as Al(OH)₃. Liming the soil led to a noticeable reduction in exchangeable Al with increasing P rates, likely due to the formation of hydroxy-Al phosphates or the addition of P as Ca(H₂PO₄)₂, which could have increased the exchangeable Ca content of the soil and shifted the exchangeable Al to an

insoluble $\text{Al}(\text{OH})_3$ form at high pH. Who reported a decrease in exchangeable Al and Aluminum saturation to appropriate levels after lime application in acidic soil.

2.7.5. Cation Exchange Capacity (CEC)

Table 4. Selected properties of the soil before liming.

Soil characteristics	Values
pH	6.1
Available P (ppm)	5.3
CEC (cmol (+) kg^{-1})	18

Soil characteristics	Values
Exchangeable acidity (cmol/ kg)	2.67
Micronutrient (mg kg^{-1})	2.67
Fe	43.34
Mn	72.29
Zn	13.57
Cu	0.38

Source: Adane Buni, Holletta ARC, 2014

Table 5. Main effects of lime and phosphorus on soil chemical properties.

Treatment	Ph	CEC	Al	Ex. acid	Av. P	Fe	Mn	Cu	Zn
Lime (kg/ha)	Cmol (+) kg^{-1}	Cmol (+) kg^{-1}	Cmol (+) kg^{-1}	mg /kg	mg /kg	mg /kg	mg /kg	mg /kg	mg /kg
0	5.03d	19.18d	0.68a	0.97a	5.36b	41.96a	70.3a	0.37d	11.67a
1250	5.64c	25.21c	0.56b	0.75b	6.70a	33.77b	58.4b	0.77b	0.19b
2500	6.14b	31.49b	0.33c	0.51c	7.04a	25.04b	46.0c	0.99a	9.78c
3750	6.72a	33.34a	0.24c	0.36c	6.67a	19.01c	34.5d	0.65c	9.75c
LSD (5%)	0.014	0.738	0.13	0.21	0.94	0.390	4.520	0.0591	0.138
CV (%)	3.01	6.24	8.12	6.43	2.04	11.56	14.73	10.11	12.38

Means within a column with the same letter(s) are not significantly different at $P \leq 0.05$. Source: Adane Buni, Holletta ARC, 2014.

The analysis of variance showed a significant impact of liming on soil CEC ($P < 0.001$). All lime treatments resulted in a noticeable increase in CEC compared to the control plots. The highest CEC value (33.34 cmol (+) kg^{-1}) was observed in the plots with the highest lime treatment, while the lowest value (19.18 cmol (+) kg^{-1}) was found in the control plots (Table 5). The increase in CEC after liming can be attributed to pH changes and the release of initially blocked negative charges by deprotonation of variable charge minerals and humic compounds due to Ca^{2+} interaction. This increased negative charge on mineral surfaces contributes to the overall increase in CEC [31].

2.7.6. Micronutrients

All limed plots showed a significant difference ($P < 0.001$) in their available Fe, Mn, and Zn content compared to the unlimed plot, with a decreasing trend as lime application rates increased. The maximum available contents observed at the unlimed plot were 41.96 mg/kg for Fe, 70.30 mg/kg for

Mn, and 11.67 mg/kg for Zn, while the minimum values at the highest liming rate of 3750 kg/ha were 19.01 mg/kg for Fe, 34.55 mg/kg for Mn, and 9.75 mg/kg for Zn (Table 5). However, the available Cu showed inconsistent changes with increasing liming. The decrease in available Fe and exchangeable Mn in the soil can be attributed to the precipitation of Fe and Mn as carbonates, oxides, or hydroxides due to the increase in pH.

3. Summary and Conclusion

The significance of lime in managing soil acidity is crucial, especially in high rainfall regions where leaching of basic cations from the topsoil can diminish crop yields. Treating soil acidity with lime is essential to mitigate harmful levels of manganese (Mn) and aluminum (Al) and support optimal crop growth in acidic soils. Lime application is vital for raising soil pH to improve nutrient availability for enhanced plant development and yield. It should be complemented with appropriate organic and inorganic fertilizers, particularly phosphorus (P) fertilizers. Identifying areas that require lime application is essential for achieving substantial

crop yield improvements. Overall, liming is a soil enhancement technique that aims to elevate soil pH to levels conducive maximum nutrient availability, plant growth, and crop production. Inorganic phosphate fertilizers and lime are commonly utilized to address these concerns, although their use may be constrained by cost and availability. Research indicates that adjusting soil acidity through lime application, specifically calcium carbonate (CaCO_3), can optimize various soil chemical parameters, including exchangeable acidity, exchangeable Al, exchangeable Ca, micronutrient concentrations, and P levels, leading to increased crop yields as crop productivity is closely tied to soil macronutrient levels.

Abbreviations

CaCO_3	Calcium Carbonate
pH	Power Hydrogen
HI	Harvest Index

Author Contributions

Lami Gebrekidan is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

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