



## RESEARCH ARTICLE

# Synergistic Amelioration of Acidic Soils: A Review of Integrated Lime, Organic, and Inorganic Fertilizer Strategies

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## Abstract

Soil acidity is a critical global constraint on agricultural productivity, causing aluminum toxicity and nutrient deficiencies that severely limit crop growth. This review synthesizes evidence on the synergistic effects of integrating lime with organic and inorganic fertilizers for soil amelioration. Data from diverse agroecosystems demonstrate that combined applications are markedly superior to any amendment alone. Lime-organic combinations significantly increase soil pH, reduce exchangeable aluminum by up to 81%, and enhance phosphorus availability by over 460%. These soil improvements catalyze substantial yield increases, with maize, wheat, and soybean yields often doubling or more. The synergy works by concurrently neutralizing acidity, complexing toxic elements, and building soil organic matter, which improves nutrient cycling, cation exchange capacity, and water retention. This integrated approach provides a sustainable pathway for transforming degraded acidic soils into productive, resilient agricultural systems, offering a practical strategy to enhance food security and resource use efficiency.

**Keywords:** Soil Acidity, Lime, Organic fertilizer.

## Introduction

Soil acidity is a major constraint to crop production in tropical and temperate regions, particularly in highly weathered and leached soils. Globally, acidic soils limit agricultural productivity on 30–40% of the world's arable land (Vista *et al.*, 2024), with Africa alone accounting for 22% of its 3.01 billion hectares affected by acidity (Zingore *et al.*, 2023). In Ethiopia, approximately 43% of the country's highly weathered soils are acidic (Beyene *et al.*, 2023), and the problem is expanding due to on-going soil degradation

(Regasa *et al.*, 2024). Regions with high rainfall, such as the north western, western, southern, and central highlands of Ethiopia, are particularly vulnerable, as excessive precipitation leaches soluble salts and basic cations from the topsoil (Regassa *et al.*, 2023). Site-specific studies in the Assosa and Wollega regions reveal that a significant proportion of tested soils are acidic, with pH levels below the optimal threshold for crop production (Regasa *et al.*, 2025b; Tadesse & Hailu, 2024). This high prevalence of acidic soils poses a major challenge to agricultural productivity, as low pH (< 5.5) reduces nutrient availability, disrupts microbial activity, and hinders root growth (Akewek, 2020). Soil acidity is a widespread and growing limitation to agricultural productivity worldwide (Yadav *et al.*, 2020). It occurs naturally in high-rainfall regions, where essential base cations like calcium (Ca<sup>2+</sup>) and magnesium (Mg<sup>2+</sup>) are leached from the soil profile. This process is significantly accelerated by the sustained use of ammonium-based nitrogen fertilizers, which release protons (H<sup>+</sup>) during nitrification (Chaudhari *et al.*, 2013). As soil pH declines, the solubility of phosphorus and molybdenum decreases, while the concentrations of phytotoxic aluminum (Al<sup>3+</sup>) and manganese (Mn<sup>2+</sup>) ions increase, creating a hostile environment that inhibits root development and function (Kochian *et al.*, 2015).

The application of lime (CaCO<sub>3</sub> or CaMg(CO<sub>3</sub>)<sub>2</sub>) is the fundamental practice for countering soil acidity. It directly neutralizes hydrogen ions, precipitates toxic Al<sup>3+</sup>, and replenishes base cations (Sparks, 2019). However, practical

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constraints such as high cost, limited access, and the need for precise, repeated application often limit its adoption and effectiveness, particularly in resource-limited farming systems (Holland *et al.*, 2018). These limitations underscore the need for integrated soil management strategies. Combining lime with organic amendments (e.g., manure, compost, biochar) and tailored inorganic fertilizers can create synergistic benefits (Ding *et al.*, 2016). Organic matter can complex toxic aluminum, improve the soil buffering capacity against pH change, and stimulate microbial activity, thereby enhancing the efficiency and longevity of the lime effect (Mesfin *et al.*, 2023). Furthermore, such integrated approaches are crucial for improving overall nutrient use efficiency, promoting long-term soil health and carbon sequestration, and mitigating the acidifying impact of mineral fertilizers (Cheng *et al.*, 2025).

Therefore, this systematic review aims to synthesize and evaluate the current body of research on the combined effects of lime with organic and inorganic fertilizers for ameliorating soil acidity and enhancing crop productivity. It will examine the biogeochemical mechanisms including cation exchange, complexation, and microbial stimulation underpinning these interactions. By consolidating existing evidence, this review seeks to identify effective and sustainable integrated management practices, providing an evidence-based framework for overcoming the persistent challenge of soil acidity.

**Methodology**

The literature evaluated in this review was identified and analyzed through a structured and comprehensive process to ensure a thorough and balanced synthesis of current knowledge. To capture the breadth of relevant research, a focused search of peer-reviewed scientific literature was conducted using major academic databases, including Web of Science, Scopus, and Google Scholar. The search was confined to publications from the year 2000 onward to prioritize contemporary findings and management practices (Figure 1).

Search terms were designed to encompass the core themes of this review. Keywords and their combinations included: *lime or liming; soil acidity or acid soil or pH; organic fertilizer or manure or compost or biochar; inorganic fertilizer or mineral fertilizer; and crop yield or productivity*. The initial search results were screened based on their titles and abstracts to select studies that explicitly investigated the combined application of lime with either organic or inorganic amendments on acidic soils (Figure 1).

The primary criteria for including a study in this synthesis were: (1) the study reported original experimental data from field, greenhouse, or pot trials; (2) it included treatments with lime in combination with another fertilizer input; and (3) it measured key outcomes related to soil acidity (e.g., soil pH, exchangeable aluminum) and/or agronomic performance

(e.g., crop growth, yield). From the pool of identified literature, relevant papers were selected for in-depth review and analysis (Figure 1).

Information on experimental conditions (e.g., soil type, climate), amendment types and application rates, and observed effects on soil properties and crop response was extracted and compared. Findings were then synthesized thematically to elucidate general trends, identify consistent patterns of synergy or interaction, and discuss the underlying mechanisms, such as cation exchange and organic matter complexation that explain the outcomes of integrated amendment strategies. This approach allows for a critical evaluation of the evidence and the formulation of practical insights for soil acidity management (Figure 1).

**Soil acidity and its Causes**

Soil acidification is a complex set of process resulting in the formation of an acid soil. In the broadest sense, it can be considered as the summation of natural and anthropogenic processes that lower down the pH of soil solution (Sparks, 2019). It has been recognized that there are several causes for soils to become acidic. For example, conditions where rainfall exceeds, leaching during most of the year, the basic soil cations are gradually depleted and replaced with cations held in colloidal soil reserves, leading to soil acidity (Nilsson, 2024). With an increase in rainfall, the contents of soluble salts are reduced to a low level, and any calcium carbonate and gypsum present are removed. With further increase in rainfall, a point is reached at which the rate of removal of bases exceeds the rate of their liberation from nonexchangeable forms. Wet climates have a greater

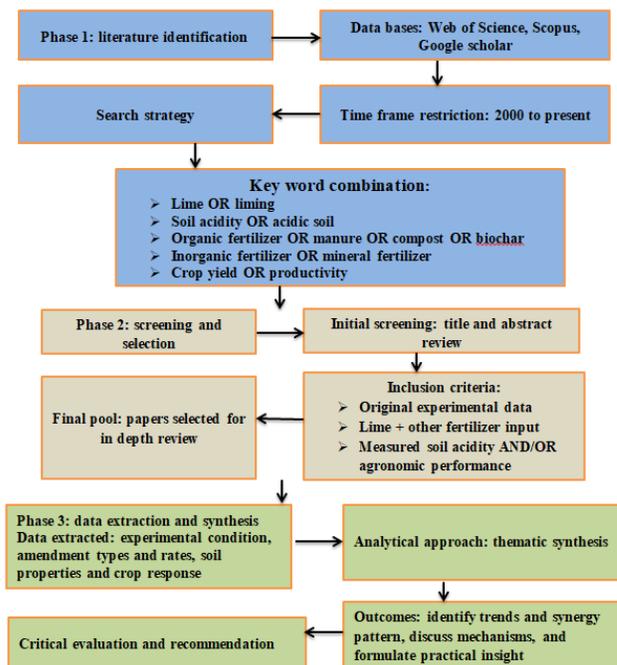


Figure 1: Systematic review process

potential for acidic soils. Over time, excessive rainfall leaches the soil profile's basic elements (Ca, Mg, Na, and K) that prevent soil acidity. High rainfall leaches soluble nutrients such as Ca and Mg which are specifically replaced by Al from the exchange sites (Agegnehu *et al.*, 2019; Laekemariam & Kibret, 2021).

Rocks containing an excess of quartz or of silica as compared to their content of basic materials or of basic elements are categorized as acid rocks; for example, granite and rhyolite (Sparks, 2019). When rocks that are deficient in bases are disintegrated or decomposed in the process of the accumulation of soil material is acidic, despite no loss of base during the process of soil formation. Soils that develop from weathered granite are likely to be more acidic than those developed from shale or limestone. There are large areas of siliceous and sandy soils produced from acid parent rocks, which have always been in need of lime (Brady and Weil, 2016).

Continuous application of inorganic fertilizer without soil test, in the end, can increase soil acidity. The use of N fertilizers in ammonia form is a source of acidification (Fageria & Baligar, 2008). When ammonium fertilizers are applied to the soil, acidity is produced, but the form of N removed by the crop is similar to that found in fertilizer. Hydrogen is added in the form of ammonia-based fertilizers ( $\text{NH}_4$ ), urea-based fertilizers [ $(\text{CO}(\text{NH}_2)_2)$ ], and as proteins (amino acid) in organic fertilizers. Transformation of such sources of N fertilizers into nitrate ( $\text{NO}_3$ ) releases hydrogen ions ( $\text{H}^+$ ) to create soil acidity. In reality, N fertilizer increases soil acidity by increasing crop yields, thereby increasing the amount of basic elements being removed. Hence, application of fertilizers containing  $\text{NH}_4$  or even adding large quantities of organic matter to a soil can ultimately increase soil acidity and lower pH (Ejersa, 2021).

The decomposition of organic matter produces  $\text{H}^+$  ions, which are responsible for acidity. The development of soil acidity from the decomposition of organic matter is insignificant in the short-term. Large quantities of carbonic acid produced by microorganisms and higher plants including through other physicochemical and biological processes are the causes of soil acidity although the effect from its dissociation is relatively small as most of it is lost to the atmosphere as  $\text{CO}_2$  (Debele, 2013; Laekemariam & Kibret, 2021). Soil organic matter or humus contains reactive carboxylic, enolic and phenolic groups that behave as weak acids. During their dissociation they release  $\text{H}^+$  ions. Further, the formation of  $\text{CO}_2$  and organic acids during the decomposition also result in replacement of bases on exchange complex with  $\text{H}^+$  ions (Agegnehu *et al.*, 2021).

Removal of elements, especially from soils with small reservoir of bases due to the harvest of high yielding crops is responsible for soil acidity. When soils are worked mechanically and crops are grown the balance is disturbed

and the soils become more acid. This is the result of base cations being removed with crops and the simultaneous increase of leaching which takes place when soils are disturbed and worked (Wakwoya *et al.*, 2022). Harvest of high-yielding crops plays the most significant role in increasing soil acidity. During growth, crops absorb basic elements such as Ca, Mg, and K to satisfy their nutritional requirements. As crop yields increase, more of these lime-like nutrients are removed from the field. Compared to the leaf and stem portions of the plant, grain contains minute amounts of these basic nutrients. Therefore, harvesting high-yielding forages such as Bermuda grass and alfalfa affects soil acidity more than harvesting grain does (Agegnehu *et al.*, 2019; Rengel, 2003).

### **Synergistic Soil Amelioration: Tackling Acidity and Its Consequences**

Soil acidity, a pervasive constraint in many of the world's agricultural regions, depresses crop productivity through a triad of interacting factors: phytotoxic aluminum ( $\text{Al}^{3+}$ ) and manganese ( $\text{Mn}^{2+}$ ) solubility, deficiency of available phosphorus (P) and base cations, and degradation of soil biological function (Kochian *et al.*, 2015). While lime application is the foundational corrective measure, evidence increasingly demonstrates that its standalone use offers a partial and often transient solution, particularly in deeply weathered soils with low buffering capacity. As illustrated by the compiled research spanning diverse agroecologies from Ethiopia to Vietnam (Table 1), a paradigm shift toward the integrated use of lime with organic and inorganic amendments is essential for a holistic and durable remediation. This synergistic strategy concurrently addresses the chemical, physical, and biological facets of soil degradation, transforming a hostile soil environment into a resilient and productive medium.

The empirical data reveal a compelling chemical synergy, where combined amendments achieve significantly greater reductions in active acidity and Al toxicity than lime or organic inputs alone. For instance, lime-vermicompost integration in Ethiopian Nitisols reduced exchangeable aluminum by 81% (Sima, 2018), while lime-manure combinations in Serbian soils immobilized Al by 4.19-fold (Dugalić *et al.*, 2025). This enhanced efficacy stems from complementary mechanisms: lime ( $\text{CaCO}_3$  or  $\text{CaMg}(\text{CO}_3)_2$ ) directly neutralizes  $\text{H}^+$  ions and precipitates  $\text{Al}^{3+}$  into non-toxic hydroxyl-Al forms, while the dissolved organic matter and humic substances released from amendments like manure or compost form stable, non-phytotoxic complexes with residual Al, further detoxifying the soil solution (Haynes & Mokolobate, 2001; Yin *et al.*, 2019). Furthermore, this co-application dramatically alleviates P deficiency (a critical yield limitation in acid soils) as evidenced by available P increases exceeding 100% in studies by Tana (2017) and

Takala (2020). Organic anions from decomposing residues compete with phosphate for binding sites on Fe and Al oxides, while the rise in pH from liming reduces P fixation, synergistically enhancing P availability for plant uptake (Regasa *et al.*, 2025a).

Beyond direct detoxification, the integrated approach fundamentally rebuilds the soil's fertility base. A consistent outcome across studies is the significant increase in effective cation exchange capacity, recorded by researchers such as Ejigu *et al.* (2023) and Sharma *et al.* (2023) (Table 1). Lime contributes base cations ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ), while the addition and decomposition of organic matter generate persistent, pH-dependent negative charges that expand the soil's nutrient-holding reservoir (Getinet *et al.*, 2024). This enhanced CEC mitigates nutrient leaching, ensuring a more sustained supply of potassium, calcium, and magnesium, as documented in the work of Akewek (2020) and Feyissa (2024). Consequently, the system moves from a state of acute nutrient deficiency and toxicity to one of balanced cation saturation, which is fundamental for long-term soil fertility and fertilizer use efficiency (Cheng *et al.*, 2025).

The biological dimension of this synergy is equally critical, though often indirectly reflected in the chemical data. The amelioration of harsh chemical conditions specifically elevated pH and reduced Al toxicity creates a favourable environment for soil microorganisms. Enhanced microbial activity accelerates the decomposition of organic amendments, releasing nutrients and generating more stable humus that further improves soil structure and CEC (Feyissa, 2024). Improved soil physical conditions, such as better aggregation and porosity from added organic matter, facilitate root exploration, allowing plants to access a greater volume of remediated soil and applied nutrients. Thus, the chemical improvements catalysed by lime-organic combinations initiate a positive feedback loop of biological activation and physical enhancement, driving the system toward greater health and resilience.

Generally, the convergence of evidence from varied pedo-climatic contexts strongly advocates for integrated soil acidity management as a cornerstone of sustainable agriculture. The synergistic application of lime with organic resources (e.g., manure, compost, biochar) and tailored mineral fertilizers delivers a comprehensive solution: it rapidly neutralizes active acidity and Al toxicity, builds long-term buffering capacity against re-acidification, enhances nutrient availability and retention, and stimulates soil biological function. This approach represents a transformative investment in soil capital. It ensures that the correction of acidity translates not into a temporary fix but into a trajectory of sustained productivity, improved climate resilience through carbon sequestration, and greater resource use efficiency objectives that are paramount for global food security in the face of environmental change (Stockmann *et al.*, 2015).

### Unlocking Nutrient Availability and Cycling

The profound constraint of soil acidity on nutrient dynamics extends far beyond the direct toxicity of aluminum. Acidic conditions severely disrupt the soil's biogeochemical cycles, locking up essential nutrients in unavailable forms and accelerating the loss of others (Obutiata Esilaba *et al.*, 2023). The data synthesized in the Table 1 demonstrates that the integrated application of lime with organic and inorganic amendments acts as a master key to unlock this nutritional gridlock. By simultaneously raising soil pH, supplying organic ligands, and replenishing nutrient stocks, these synergistic treatments transform infertile, nutrient-fixing soils into productive, nutrient-cycling systems, fundamentally enhancing the efficiency of fertilizer inputs.

Phosphorus (P) availability is a primary beneficiary of this synergy, as consistently shown by the significant increases in available P across diverse studies. In Ethiopian Nitisols, combinations of lime with compost and chemical P fertilizer raised available P from 6.68 to 15.05 mg/kg (Tana, 2017), while lime with coffee husk compost triggered a 462.4% increase over the control (Takala, 2020). This dramatic effect is achieved through a dual mechanism: lime increases pH, which reduces the concentration of reactive  $\text{Al}^{3+}$  and  $\text{Fe}^{3+}$  ions that strongly adsorb phosphate, while organic amendments release compounds that compete with phosphate for these same adsorption sites (Ayenew *et al.*, 2018; Wang *et al.*, 2015). Furthermore, organic acids from decomposing manure or compost can solubilize fixed mineral P, effectively recycling legacy P within the soil profile (Yan *et al.*, 2013). This synergistic P mobilization reduces the agronomic P requirement and improves the recovery efficiency of applied mineral P fertilizers.

The synergy also critically enhances the availability and retention of base cations such as calcium (Ca), magnesium (Mg), and potassium (K). Acidic soils are typically depleted of these cations due to leaching, but integrated management provides both a source and a sink. Lime directly supplies Ca and often Mg, while organic amendments like vermicompost and farmyard manure are rich sources of K and secondary nutrients (Ejigu *et al.*, 2023; Feyissa, 2024; Terefe *et al.*, 2024). Crucially, the concurrent increase in CEC, documented by multiple studies (e.g., Abebe *et al.*, 2024; Bekele *et al.*, 2018; Ejigu *et al.*, 2023; Sharma *et al.*, 2023), creates a larger and more effective exchange complex to retain these supplied cations against leaching loss. This creates a positive cycle where improved nutrient retention supports greater plant biomass production, which in turn returns more organic residues to the soil, further building CEC and long-term fertility (Holland *et al.*, 2018).

Beyond macronutrients, integrated amelioration optimizes the availability of micronutrients, navigating a critical balance. While liming alone can induce deficiencies of zinc (Zn) and copper (Cu) by overly increasing pH, the

**Table 1:** Effects of Integrated Lime with Organic and Inorganic Fertilizers on Soil Properties

Reference	Country	Soil Type	Treatments	Key Finding (Soil Properties)
(Sima, 2018)	Ethiopia	Nitisols	Lime, VC, TSP	pH increased from 4.83 to 6.05; exchangeable Al decreased from 1.70 to 0.09 cmolc kg <sup>-1</sup> ; reduced soil acidity by 81%
(Garamu, 2020)	Brazil	Oxisols	Dolomite, Manure	pH increase correlated with reduced exchangeable Al
(Dugalić <i>et al.</i> , 2025)	Serbia		NPK, Lime, Manure	Increased pH by 1.54 units; immobilized Al by 4.19 fold (1.15 to 0.22 cmol. kg <sup>-1</sup> ); Increased Av. P from 9 to 16.6 mg/kg
(Tana, 2017)	Ethiopia	Nitisols	Compost, Lime and chemical P fertilizer	Av P increased from 6.68 to 15.05 mg/kg; Ex Al decreased from 2.41 to 0.51 cmol/kg
(Takala, 2020)	Ethiopia	Acrisols	Coffee husk compost & lime	Increased pH from 4.71 to 5.92; Decreased exchangeable acidity from 3.2 to 0.2; Increased available P by 462.4% over control
(Feyissa, 2024)	Ethiopia	Nitisols	Chemical P, vermicompost (VC), and lime	Increased soil pH and Av. P; Decreased exchangeable acidity; Increased exchangeable Ca, Mg and K; Increased effective CEC; Reduced micronutrients (Fe, Mn, Zn and Cu)
(Ejigu <i>et al.</i> , 2023)	Ethiopia	Nitisols	Lime, FYM and chemical N fertilizer	Increased ex. Ca (7.97 to 12.78), Mg (1.28 to 2.18) and K (0.19 to 0.57); Increased CEC from 19.91 to 32 cmol (+) kg <sup>-1</sup>
(Meena & Prakasha, 2021)	India	Sand clay loam	Biochar, lime and fertilizer	Decreased exchangeable aluminium (1.34 to 0.83), acidity (1.72 to 1.05), and total acidity (3.21 to 1.54 cmol (+) kg <sup>-1</sup> )
(Melese & Yli-halla, 2016)	Ethiopia	Luvisols	Lime, wood ash, manure and mineral P fertilizer	Increased pH from 4.89 to 5.71; Increased CEC from 25.7 to 26.71; Increased Av. P from 5.7 to 13.4 mg/kg
(Takala <i>et al.</i> , 2025)	Ethiopia	Nitisols	Biochar, lime and NP	Increased pH and available P; Reduced exchangeable acidity
(Khoi <i>et al.</i> , 2010)	Vietnam	Typic Sulfaquepts	Lime and compost	Significantly increased soil pH; decreased titratable acidity, exchangeable Al <sup>3+</sup> and dissolved Al dramatically
(Dereje <i>et al.</i> , 2019)	Ethiopia		Lime and Phosphorus Fertilizer	Significantly increased soil pH, Av. P and exchangeable cations; significantly decreased soil exchangeable Al
(Akewek, 2020)	Ethiopia	Nitisols	Lime and vermicompost	Increased soil pH from 5.1 to 5.8, Av. P from 3.67 to 13.27 mg/kg; Reduced exchangeable acidity from 2.44 to 0.33 cmol/kg; Increased exchangeable Ca, Mg, K, Na, CEC and PBS
(Sharma <i>et al.</i> , 2023)	India	Alfisols	FYM, Lime and Fertilizers	Increased soil pH from 5.47 to 5.75, CEC from 11.72 to 14.20 cmolc kg <sup>-1</sup> ; increased available phosphorous, exchangeable calcium and magnesium; Decreased exchangeable acidity, total potential acidity, and other acidity measures
(Otieno <i>et al.</i> , 2018)	Kenya	-	Farmyard Manure, Lime and Inorganic Fertilizer	Increased soil pH by 2.59 units, available phosphorus from 0.11 to 0.54% and available potassium from 1.35 to 2.70%
(Kisinyo <i>et al.</i> , 2014)	Kenya	Acrisols	Lime and P fertilizer	Increased soil pH, available P and exchangeable cations
(Adisu <i>et al.</i> , 2019)	Ethiopia	Nitisols	Lime and vermicompost	Soil pH increased from 5.31 - 5.86; exchangeable acidity decreased from 5.46 - 2.85 cmol (+) kg <sup>-1</sup>

addition of organic matter modulates this effect. As noted by Regasa *et al.* (2025a) and Feyissa (2024) combined treatments increased pH and major nutrients while reducing soluble Fe, Mn, Zn, and Cu. Organic matter forms stable complexes with these micronutrients, maintaining a pool of organically-bound nutrients that are protected from fixation yet slowly available to plants and microbes, preventing acute deficiency (Kang *et al.*, 2009). This buffering of micronutrient availability exemplifies the sophisticated regulation that synergistic management provides, ensuring a more

balanced and complete nutritional environment for crops.

Ultimately, the most significant unlocking is of the soil's inherent biological nutrient cycling engine. The correction of chemical stressors (low pH, Al toxicity) and the provision of a balanced organic substrate stimulate microbial and enzymatic activity (Dawid, 2021). Enhanced microbial biomass drives the mineralization of nitrogen and sulfur from organic amendments, synchronizing nutrient release with crop demand. Improved soil structure from added organic matter fosters a larger and more active root system,

allowing plants to more effectively intercept and uptake cycled nutrients. Therefore, the synergy between lime and organic inputs does not merely add nutrients to the soil; it revitalizes the biological pump that continuously converts organic and fixed nutrients into plant-available forms, establishing a resilient and self-sustaining foundation for crop nutrition (Stockmann *et al.*, 2015). This shift from a paradigm of external nutrient input to one of managed internal nutrient cycling is essential for the sustainability of agricultural systems on acidic soils.

### Boosting Crop Productivity: From Healthy Soil to High Yields

The ultimate measure of any soil management strategy is its impact on crop productivity. The transformation of a chemically hostile, nutrient-poor soil into a fertile medium,

as detailed in the preceding analysis, directly catalyses profound improvements in plant growth and yield, as consistently was demonstrated in the Table 2. The data, spanning continents and cropping systems, reveal that the synergistic application of lime with organic and inorganic fertilizers is not merely an agronomic adjustment but a fundamental catalyst for unlocking genetic yield potential. The remarkable yield increases ranging from 65% in maize (Sima, 2018) to over 290% in other maize systems (Manoj-Kumar *et al.*, 2012) stem directly from the alleviation of the multiple, interconnected stresses that characterize acidic soils. By neutralizing toxicity and correcting nutrient deficiencies simultaneously, integrated management allows plants to shift resources from stress tolerance to productive growth, establishing a robust foundation for high yields.

**Table 2: Effects of Integrated Lime with Organic and Inorganic Fertilizers on Crop Productivity**

Reference	Country	Soil Type	Crop	Treatments	Key Finding (Yield and Productivity)
(Bekele <i>et al.</i> , 2018)	Ethiopia	Nitisols	Maize	Lime, VC, TSP	Yield increased by 65% over control (From 2.18 to 4.87 ton/ha)
(Garamu, 2020)	Brazil	Oxisols	Soybean	Dolomite, Manure	Soybean yield doubled with integrated application
(Dugalić <i>et al.</i> , 2025)	Serbia		Maize	NPK, Lime, Manure	Yield increased by 30.7% over control
(Manoj-Kumar <i>et al.</i> , 2012)	India	Alfisols	Maize	Lime, NPK, FYM	Combined lime, NPK FYM increased yield by 291% over control; 100% NPK + Liming increased yield by 147%
(Getinet <i>et al.</i> , 2024)	Ethiopia	Nitisols	Wheat	Lime, FYM and chemical N fertilizer	Increased yield from 2162.3 to 3203.8 kg/ha; Increased plant height and spike length
(Feyissa, 2024)	Ethiopia	Nitisols	Wheat	Chemical P, vermicompost (VC), and lime	Increased grain yield by 165.2% over control; Improved Grain N, crude protein, wet gluten and hectolitre weight
(Ejigu <i>et al.</i> , 2023)	Ethiopia	Nitisols	Wheat	Lime, FYM and chemical N fertilizer	Increased grain yield by 97.5% over control; Increased plant height, spike length, and grains per spike
(Meena & Prakasha, 2021)	India	Sand clay loam	Rice and Cowpea	Biochar, lime and fertilizer	Rice grain yield increased by 37.90%; Yield of cowpea increased by 33.57% over farmer practice
(Takala <i>et al.</i> , 2025)	Ethiopia	Nitisols	Maize	Biochar, lime and NP	Increased yield from 3710.2 to 6448.2 kg/ha
(Dereje <i>et al.</i> , 2019)	Ethiopia		Sorghum	Lime and Phosphorus Fertilizer	Increased yield from 554.8 to 2469.1 kg/ha
(Tshiabukole <i>et al.</i> , 2022)	RDC	Orthic feral	Maize	Lime, NPK and Urea	Improved maize growth and yield performance
(Asrat <i>et al.</i> , 2020)	Ethiopia	Nitisols	Faba bean	Lime, manure and kitchen ash	Increased faba bean yield from 1343 to 2268 kg/ha; Improved agronomic and yield performance
(Akewek, 2020)	Ethiopia	Nitisols	Maize	Lime and vermicompost	Increased maize yield from 2.97 to 7.99 ton/ha; Increased plant height, DPM, cob length, TGW, NSPC and reduced days to tasseling/silking
(Otieno <i>et al.</i> , 2018)	Kenya	-	Soybean	Farmyard Manure, Lime and Inorganic Fertilizer	Significantly increased soybean height, leaf area and aboveground biomass; Improved uptake of P and K nutrients
(Kisinyo <i>et al.</i> , 2014)	Kenya	Acrisols	Maize	Lime and P fertilizer	Increased maize yield from 0.52 to 2.313 ton/ha
(Adisu <i>et al.</i> , 2019)	Ethiopia	Nitisols	Soybean	Lime and vermicompost	Increased yield and yield components of soybean

The primary pathway to enhanced productivity is the removal of aluminum ( $\text{Al}^{3+}$ ) toxicity, which directly inhibits root elongation and function, severely limiting water and nutrient foraging. The combined treatments documented in the Table 2, such as lime with manure (Dugalić *et al.*, 2025) or vermicompost (Akewek, 2020), effectively precipitate and complex Al, facilitating the development of deep, healthy root systems. This improved root architecture enables crops to access moisture and nutrients from a larger soil volume, enhancing drought resilience and nutrient uptake efficiency (Kochian *et al.*, 2015). The resulting vigorous vegetative growth is evident in the consistent reports of increased plant height, leaf area, and biomass, as seen in soybean (Otieno *et al.*, 2018) and maize (Akewek, 2020). A healthy root system is the indispensable engine for capturing the benefits of improved soil chemistry.

Concurrently, the synergistic strategy ensures a balanced and abundant nutrient supply, which directly translates into superior yield components and grain quality. The dramatic mobilization of phosphorus, a critical yield-limiting nutrient in acid soils, is a key driver. Enhanced P availability supports better flowering, grain set, and seed development, contributing directly to higher grain numbers and weight. This is reflected in studies on wheat, where combined lime and organic amendments significantly increased grains per spike and thousand-grain weight (Ejigu *et al.*, 2021, 2023; Feyissa, 2024; Terefe *et al.*, 2024). Furthermore, improved nitrogen use efficiency, facilitated by better root health and microbial mineralization of organic N sources, supports greater biomass and protein synthesis. Feyissa (2024) specifically noted that integrated management not only boosted wheat yield by 165% but also improved grain nitrogen, crude protein, and hectolitre weight, demonstrating a direct link between soil health and nutritional crop quality.

The agronomic benefits extend beyond yield maximization to include greater cropping system stability and resource use efficiency. The data show positive responses across a wide range of crops including cereals (maize, wheat, sorghum), legumes (soybean, faba bean), and even rice in acidic lowlands (Meena & Prakasha, 2021) indicating the broad applicability of the approach. By building soil organic matter and CEC, integrated management enhances the soil's buffering capacity, making crop production less vulnerable to fluctuations in rainfall or minor errors in fertilizer timing. This creates a more predictable and resilient production environment. Moreover, the improved efficiency of applied fertilizers, as nutrients are retained rather than lost to leaching or fixation, reduces the economic and environmental cost per unit of grain produced, a critical consideration for sustainable intensification (Alley & Vanlauwe, 2009).

Generally, the empirical yield data provide unequivocal evidence that soil health is the bedrock of crop productivity.

The integrated management of acidity through lime-organic-fertilizer combinations creates a virtuous cycle: improved soil chemistry fosters healthy root development, which enhances nutrient and water capture, leading to vigorous growth and optimized yield formation. This synergy moves beyond addressing single limitations to create a holistic, productive soil ecosystem. Therefore, boosting crop productivity on acidic lands is not solely a question of applying more inputs but of strategically managing the soil environment to allow crops and inputs to perform at their peak. Investing in these synergistic soil amendments is, fundamentally, an investment in realizing stable and high yields, ensuring food security and farmer livelihoods in some of the world's most challenging agricultural landscapes.

### Conclusion and Agronomic Implications

This review consolidates robust evidence that the integrated application of lime with organic and inorganic fertilizers represents a transformative strategy for sustainable management of acidic soils. Empirical data from diverse global agroecosystems confirm that this synergistic approach is markedly superior to the application of any single amendment. The combined treatments work through complementary biogeochemical mechanisms: lime rapidly neutralizes active acidity and precipitates toxic aluminum, while organic matter complexes residual toxins, enhances nutrient retention by boosting cation exchange capacity, and stimulates microbial activity. This creates a virtuous cycle where improved soil chemistry fosters healthy root development, which in turn enhances nutrient and water use efficiency, leading to dramatic increases in crop productivity, with documented yield gains often exceeding 100%.

The agronomic implications of these findings are profound and directly actionable. First, extension services and policy frameworks must shift from promoting lime as a standalone remedy to advocating for context-specific integrated packages. Recommendations should provide tailored combinations of lime, locally available organic resources (e.g., manure, compost, crop residues), and balanced mineral fertilizers, with application rates calibrated to initial soil pH, texture, and organic matter content. Second, there is a critical need for long-term field demonstrations and participatory research with farmers. Demonstrating the economic advantage where the significant initial investment in lime and organic inputs is offset by substantial and sustained yield increases and reduced fertilizer costs over time is essential for adoption, particularly among resource-constrained smallholders. Finally, this strategy aligns with climate-smart agriculture objectives. By building soil organic carbon and improving nutrient efficiency, it enhances system resilience, contributes to carbon sequestration, and reduces the environmental footprint of agriculture.

Ultimately, managing soil acidity is not merely a chemical correction but an investment in foundational soil health. Adopting these synergistic management practices enables a transition from degraded, input-responsive systems to productive, buffered, and biologically active agroecosystems. This paradigm is essential for securing stable yields, improving livelihoods, and ensuring long-term food security in regions constrained by soil acidity. Future research should focus on optimizing combination ratios, evaluating the long-term economic returns, and breeding crop varieties that can maximize benefits from these revitalized soil conditions.

### Competing Interests

The author declares no competing interests.

### Data Availability

The data supporting this study are fully available within the manuscript.

### References

- Abebe, A., Yli-Halla, M., & Wogi, L. (2024). Effects of lime, vermicompost, and blended fertilizer on maize (*Zea mays* L.) postharvest selected soil chemical properties in Assosa District, north-western Ethiopia. *Big Data in Agriculture*, 6(1), 36–43. <https://doi.org/10.26480/bda.01.2024.36.43>
- Adisu, T., Wogi, L., & Feyisa, T. (2019). Soybean (*Glycine max* L.) Response to Lime and Vermicompost Amelioration of Acidic Nitisols of Assosa, North Western Ethiopia. *International Journal of Plant & Soil Science*, 27(2), 1–18. <https://doi.org/10.9734/ijps/2019/v27i230072>
- Akewek, W. N. (2020). Responses of Acidic Soil and Maize to Lime and Vermicompost Application at Lalo Asabi District, Western Ethiopia. In *MSc Thesis Submitted to the School of Natural Resources Management and Environmental Sciences, Postgraduate Programs Directorate Haramaya University*. Haramaya University, Ethiopia.
- Alley, M. M., & Vanlauwe, B. (2009). *The Role of Fertilizers in Integrated Plant Nutrient Management*. IFA- International Fertilizer Industry Association.
- Asrat, M., Yli-halla, M., & Abate, M. (2020). *Effects of Lime, Manure and Kitchen Ash Application on Yield and Yield Components of Faba Bean (Vicia faba L.) on Acidic Soils of Gozamin District*. 8(2), 17–28. <https://doi.org/10.11648/j.jps.20200802.11>
- Ayenew, B., Tadesse, A. M., Kibret, K., & Melese, A. (2018). Chemical forms of phosphorous and physicochemical properties of acid soils of Cheha and Dinsho districts, southern highlands of Ethiopia. *Environmental Systems Research*, 7(1). <https://doi.org/10.1186/s40068-018-0118-9>
- Bekele, A., Kibret, K., Bedadi, B., Balemi, T., & Yli-halla, M. (2018). *Vermicompost and chemical P fertilizer on yield of maize and soil properties in Ebantu District, Western Highlands of Ethiopia* Effects of lime, vermicompost and chemical P fertilizer on yield of maize in Ebantu District, Western highlands of Ethiopia. <https://doi.org/10.5897/AJAR2017.12949>
- Bekele, A., Kibret, K., Bedadi, B., Balemi, T., & Yli-Halla, M. (2018). Effects of lime, vermicompost and chemical P fertilizer on yield of maize in Ebantu District, Western highlands of Ethiopia. *African Journal of Agricultural Research*, 13(10), 477–489.
- Beyene, S., Regassa, A., Mishra, B. B., & Haile, M. (2023). *The soils of Ethiopia*. Springer.
- Chaudhari, P. R., Ahire, D. V., Ahire, V. D., Chkravarty, M., & Maity, S. (2013). Soil Bulk Density as related to Soil Texture, Organic Matter Content and available total Nutrients of Coimbatore Soil. *International Journal of Scientific and Research Publications*, 3(1), 2250–3153. [www.ijrsrp.org](http://www.ijrsrp.org)
- Cheng, J., Yang, C.-Z., Zhang, L., Lin, Z.-J., Dang, Y. P., Zhao, X., & Zhang, H.-L. (2025). The competitive effects of crop straw return and nitrogen fertilization on soil acidification. *Agriculture, Ecosystems & Environment*, 388, 109638.
- Dawid, J. (2021). Effects of Lime and Compost on Acidic Soil Amelioration and Grain Yield of Maize at Jimma, Southwestern Ethiopia. *Journal of Natural Sciences Research*, 12(3), 16–23. <https://doi.org/10.7176/jnsr/12-3-03>
- Dereje, G., Tamene, D., & Anbesa, B. (2019). Effect of Lime and Phosphorus Fertilizer on Acid Soil Properties and Sorghum Grain Yield and Yield Components at Assosa in Western Ethiopia. *World Research Journal of Agricultural Sciences*, 6(2), 167–175.
- Ding, Y., Liu, Y., Liu, S., Li, Z., Tan, X., Huang, X., Zeng, G., Zhou, L., & Zheng, B. (2016). Biochar to improve soil fertility. A review. *Agronomy for Sustainable Development*, 36(2). <https://doi.org/10.1007/s13593-016-0372-z>
- Dugalić, M., Rakočević-Bošković, L., Latković, D., Rajičić, V., Terzić, D., & Životić, L. (2025). Effect of Lime, Mineral Fertilizer and Manure on Soil Characteristics and Yield of Four Maize Hybrids. *Agronomy*, 15(3), 1–19. <https://doi.org/10.3390/agronomy15030542>
- Ejigu, W., G.Selassie, Y., Elias, E., & Damte, M. (2021). Integrated fertilizer application improves soil properties and maize (*Zea mays* L.) yield on Nitisols in Northwestern Ethiopia. *Heliyon*, 7(2), 13–32. <https://doi.org/10.1016/j.heliyon.2021.e06074>
- Ejigu, W., Selassie, Y. G., & Elias, E. (2023). Integrated use of compost and lime enhances soil properties and wheat (*Triticum aestivum* L.) yield in acidic soils of Northwestern Ethiopia. *International Journal of Recycling of Organic Waste in Agriculture*, 193–207. <https://doi.org/10.30486/IJROWA.2022.1941048.1343>
- Feyissa, R. L. (2024). *Productivity and Grain Quality of Bread Wheat (Triticum aestivum L.) Genotypes as Influenced by Lime, Mineral Fertilizers, and Vermicompost on Acid Soils of Guto-Gida and Welmera Districts, Oromia Region, Ethiopia* Postgraduate Program Directorate (Issue November). Haramaya University.
- Garamu, T. (2020). Effect of different source and rates of biochar application on the yield and yield components of mungbean on the acidic soil in western Ethiopia. *International Journal of Research in Agronomy*, 3(1), 01–07. <https://doi.org/10.33545/2618060x.2020.v3.i1a.23>
- Getinet, H., Abera, K., & Lulie, B. (2024). *Evaluating Integrated Application of Lime and Organic Materials on Yield and Yield Components of Wheat S Under Acid Soils of Aneded District, Northwest Ethiopia*. 11(2), 15–21.
- Haynes, R. J., & Mokolobate, M. S. (2001). Amelioration of Al toxicity and P deficiency in acid soils by additions of organic residues: A critical review of the phenomenon and the mechanisms involved. *Nutrient Cycling in Agroecosystems*, 59(1), 47–63. <https://doi.org/10.1023/A:1009823600950>

- Holland, J. E., Bennett, A. E., Newton, A. C., White, P. J., McKenzie, B. M., George, T. S., Pakeman, R. J., Bailey, J. S., Fornara, D. A., & Hayes, R. C. (2018). Liming impacts on soils, crops and biodiversity in the UK: A review. *Science of the Total Environment*, 610–611, 316–332. <https://doi.org/10.1016/j.scitotenv.2017.08.020>
- Kang, J., Hesterberg, D., & Osmond, D. L. (2009). Soil Organic Matter Effects on Phosphorus Sorption: A Path Analysis. *Soil Science Society of America Journal*, 73(2), 360–366. <https://doi.org/10.2136/sssaj2008.0113>
- Khoi, C. M., A, V. T. G., Nguyen, P., Trung, M., & B, S. I. N. (2010). Effects of compost and lime amendment on soil acidity and N availability in acid sulfate soil. *World*, August, 52–55.
- Kisinyo, P. O., Opala, P. A., Gudu, S. O., Othieno, C. O., Okalebo, J. R., Palapala, V., & Otinga, A. N. (2014). Recent advances towards understanding and managing Kenyan acid soils for improved crop production. *African Journal of Agricultural Research*, 9(31), 2397–2408. <https://doi.org/10.5897/ajar2013.8359>
- Kochian, L. V., Pi, M. A., & Liu, J. (2015). *Plant Adaptation to Acid Soils: The Molecular Basis for Crop Aluminum Resistance*. January, 1–28. <https://doi.org/10.1146/annurev-arplant-043014-114822>
- Manoj-Kumar, S., Hazarika, B. U., Choudhury, T. R., Verma, B. C., Verma, B. C., & Bordoloi, L. J. (2012). Liming and integrated nutrient management for enhancing maize productivity on acidic soils of northeast India. *Ind J Hill Farming*, 25(1), 35–37.
- Meena, H. M., & Prakasha, H. C. (2021). The impact of biochar, lime and fertilizer on soil acidity and microbiological properties and their relationship with yield of rice and cowpea in an acidic soil of Southern India. *Journal of Plant Nutrition*, 0(0), 1–11. <https://doi.org/10.1080/01904167.2021.1952225>
- Melese, A., & Yli-halla, M. (2016). *Effects of applications of lime, wood ash, manure and mineral P fertilizer on the inorganic P fractions and other selected soil chemical properties on acid soil of Farta District, Northwestern highland of Ethiopia*. 11(2), 87–99. <https://doi.org/10.5897/AJAR2015.9632>
- Mesfin, G., Zewide, I., & Jembere, A. (2023). *Physicochemical Characterization of Vermicompost and its Effect on Acidic Soils in Ethiopia*. 14, 37–49. <https://doi.org/10.58414/SCIENTIFICTEMPER.2023.14.1>
- Obutiati Esilaba, A., Opala, P., & Muindi, E. M. (2023). *Soil Acidity and Liming Handbook for Kenya* (Issue August). <https://www.researchgate.net/publication/373247387>
- Otieno, H. M. O., Chemining'wa, G. N., & Zingore, S. (2018). Effect of Farmyard Manure, Lime and Inorganic Fertilizer Applications on Soil pH, Nutrients Uptake, Growth and Nodulation of Soybean in Acid Soils of Western Kenya. *Journal of Agricultural Science*, 10(4), 199. <https://doi.org/10.5539/jas.v10n4p199>
- Regasa, A., Haile, W., & Abera, G. (2024). Soil acidity and fertility status of surface soils under different land uses in Sayo district of. *PLOS ONE*, 19(12), 1–19. <https://doi.org/10.1371/journal.pone.0316009>
- Regasa, A., Haile, W., & Abera, G. (2025a). Effects of lime and vermicompost application on soil physicochemical properties and phosphorus availability in acidic soils. *Scientific Reports*, 1–17. <https://doi.org/https://doi.org/10.1038/s41598-025-02053-4>
- Regasa, A., Haile, W., & Abera, G. (2025b). Variation in soil acidity across different land uses, soil types and altitudinal gradients in Western. *Scientific Reports*, 1–15.
- Regassa, A., Kibret, K., Selassie, Y. G., Kiflu, A., & Tena, W. (2023). Soil properties. In *The Soils of Ethiopia* (pp. 111–156). Springer.
- Sharma, A., Sharma, R. P., & Kumar, N. K. S. R. (2023). Effect of FYM, Lime and Fertilizers on Forms of Soil Acidity and Relationship with Soil Properties in Acid Alfisol. *Indian Journal of Ecology*, 50, 306–312.
- Sima, A. B. (2018). Evaluation of Soil Acidity And Effects of Amendments on Selected Soil Properties And Yield Of Maize (Z Ea Mays L.) In Ebantu District, Western Highlands of Ethiopia. *PhD DISSERTATION*, June.
- Sparks, D. L. (2019). Fundamentals of soil chemistry. *Encyclopedia of Water: Science, Technology, and Society*, 1–11.
- Stockmann, U., Adams, M. A., Crawford, J. W., Field, D. J., Henakaarchchi, N., Jenkins, M., Minasny, B., Mcbratney, A. B., Remy, V. De, Courcelles, D., Singh, K., Wheeler, I., Abbott, L., Angers, D. A., Baldock, J., Bird, M., Brookes, P. C., Chenu, C., Jastrow, J. D., ... Zimmermann, M. (2015). The knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agriculture, Ecosystems and Environment*, 164(2013), 80–99. <https://doi.org/10.1016/j.agee.2012.10.001>
- Tadesse, A., & Hailu, W. (2024). Causes and Consequences of Land Degradation in Ethiopia: A Review. *International Journal of Science and Qualitative Analysis*, 10(1), 10–21. <https://doi.org/10.11648/j.ijjsqa.20241001.12>
- Takala, B. (2020). *Ameliorative Effects of Coffee Husk Compost and Lime Amendment on Acidic Soil of Haru, Western Ethiopia*. 4(1), 141–150. <https://doi.org/10.36959/624/439>
- Takala, B., Teshale, E., & Bayata, A. (2025). *Integrated Use of Biochar and Lime Enhances Soil Properties and Maize Yield in Acidic Soil of Jimma Zone, Southwestern Ethiopia*. January. <https://doi.org/10.11648/j.sjac.20251301.11>
- Tana, T. (2017). *Application of Compost, Lime and P Fertilizer on Selected Soil Properties and P Use Efficiency of Maize in Acidic Soil of Assosa, Western Ethiopia Effect of Compost, Lime and P on Selected Properties of Acidic Soils of Assosa*. January. <https://doi.org/10.9734/JEAI/2017/36976>
- Terefe, Z., Feyisa, T., Molla, E., & Ejigu, W. (2024). Effects of vermicompost and mineral fertilizers on soil properties, malt barley (*Hordeum distichum* L.) yield, and economic benefits. *Agrosystems, Geosciences and Environment*, 7(3), 1–15. <https://doi.org/10.1002/agg2.20550>
- Tshiabukole, J. P. K., Khonde, G. P., Phongo, A. M., Ngoma, N., Vumilia, R. K., & Kankolongo, A. M. (2022). Liming and Mineral Fertilization of Acid Soils in Maize Crop within the Savannah of Southwestern of Democratic Republic of Congo. *OALib*, 09(03), 1–10. <https://doi.org/10.4236/oalib.1108412>
- Vista, S. P., Gaihre, Y. K., & Dahal, K. R. (2024). Plant nutrient availability in acid soil and management strategies. In *Climate Change and Soil-Water-Plant Nexus: Agriculture and Environment* (pp. 331–353). Springer.
- Wang, H., Zhu, J., Fu, Q. L., Xiong, J. W., Hong, C., Hu, H. Q., & Violante, A. (2015). Adsorption of phosphate onto ferrihydrite and ferrihydrite-humic acid complexes. *Pedosphere*, 25(3), 405–414. [https://doi.org/10.1016/S1002-0160\(15\)30008-4](https://doi.org/10.1016/S1002-0160(15)30008-4)
- Yadav, D. S., Jaiswal, B., Gautam, M., & Agrawal, M. (2020). Soil Acidification and its Impact on Plants. In P. Singh, S. K. Singh, & S. M. Prasad (Eds.), *Plant Responses to Soil Pollution* (pp. 1–26). Springer Singapore. [https://doi.org/10.1007/978-981-15-4964-9\\_1](https://doi.org/10.1007/978-981-15-4964-9_1)
- Yan, X., Wang, D., Zhang, H., Zhang, G., & Wei, Z. (2013). Organic

- amendments affect phosphorus sorption characteristics in a paddy soil. *Agriculture, Ecosystems and Environment*, 175, 47–53. <https://doi.org/10.1016/j.agee.2013.05.009>
- Yin, D., Guo, X., Ding, G., Jin, L., Man, X., Yang, K., Zhang, Y., & Zhang, P. (2019). Effects of Biochar Based Fertilizer on Soil Nutrient Content and Maize Yield of Acidic Soil in Heilongjiang Province. *Advances in Bioscience and Biotechnology*, 10(06), 133–149. <https://doi.org/10.4236/abb.2019.106010>
- Zingore, S., Desalegn, T., Diallo, A., Amede, T., Njoroge, S., Diallo, M., Wanjiru, L., & Botillen, Ø. (2023). The Implication of Soil Acidity and Management Options for Sustainable Crop Production in Africa. Accessed March, 29, 2024.