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Soil acidification: sources, processes, impacts on soil properties, nutrient dynamics, crop health, and yield – a review with evidence from Ethiopia and Sub-Saharan Africa

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Abstract

Soil acidity is a major constraint to agricultural yield in Ethiopia and Sub-Saharan Africa, affecting a large proportion of arable land. This review provides a comprehensive synthesis of soil acidification, its sources, and its impacts on agricultural ecosystems, with evidence from Ethiopia and Sub-Saharan Africa. Natural factors such as parent material weathering and high rainfall, together with agricultural practices including the continuous use of ammonium-based fertilizers and nutrient mining, accelerate soil acidification processes. Soil acidity profoundly alters soil chemical, physical, and biological properties by disrupting nutrient dynamics, including nutrient fixation, leaching, and transformation, which reduce the plant-available pools of essential nutrients such as phosphorus, calcium, and magnesium, while increasing the solubility of toxic metals such as aluminum (Al^{3+}) and manganese (Mn). Aluminum toxicity impairs root development and nutrient uptake, negatively affecting crop health and leading to substantial reductions in crop yield and quality. Advances in understanding the physiological mechanisms of aluminum toxicity have supported the development of acid-tolerant crop varieties. Effective agronomic management strategies include liming, integrated nutrient management, application of organic amendments such as biochar, and the use of acid-tolerant crops, alongside emerging technological approaches. However, adoption remains constrained by the high cost of lime and limited extension services. Future research should prioritize cost-effective soil amendments and breeding for enhanced acid tolerance, while policy interventions should strengthen extension services and improve farmers' access to inputs. This review highlights the importance of integrated and sustainable approaches to managing soil acidity to improve crop health, yield, and long-term food security in vulnerable regions.

Keywords: *Soil acidity, Ethiopia, Sub-Saharan Africa, nutrient dynamics, aluminum toxicity, liming, biochar, acid-tolerant crops*

Introduction

Soil acidity is a pervasive form of degradation that severely impedes agricultural productivity globally, especially in regions such as the Ethiopian Highlands, where it affects nearly 43% of arable land. Similarly, in Sub-Saharan Africa, an estimated 30–50% of agricultural soils are affected by acidity, with variations depending on regional environmental conditions and land management practices. Over the past decade, the extent of acidic soils has expanded, and soil pH has declined in many areas, reflecting intensifying acidifycation (Warke et al., 2024; Tully et al., 2015). Natural causes of soil acidity include the decomposition of organic matter and the weathering of parent materials, which release hydrogen ions (H^+) into the soil solution and deplete essential basic cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+), thereby lowering soil pH and reducing nutrient availability for plants (Farooqi et al., 2024). When combined with high rainfall and leaching-prone soils, these natural processes accelerate acidification and compromise long-term soil fertility. However, improper agricultural practices, such as the continuous application of ammonium-based fertilizers, are major accelerators, as nitrification

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releases additional hydrogen ions (H^+) into the soil (Arnall, 2024). This, combined with crop removal of basic cations and acid rain, overwhelms the soil's buffering capacity, leading to the leaching of essential cations like calcium, magnesium, and potassium (Farooqi et al., 2024). Soil acidification extensively reduces overall soil fertility by decreasing nutrient availability, altering microbial communities, and increasing metal solubility (Warke et al., 2024). The optimal pH for most essential nutrients (nitrogen, phosphorus, potassium) is 6.0-7.0 (Khaled and Sayed, 2023). In acidic soils (pH < 5.5), essential macronutrients such as phosphorus, calcium, and magnesium become significantly less available due to precipitation or adsorption onto soil particles (Warke et al., 2024; Khaled and Sayed, 2023). Conversely, acidic conditions increase the solubility of toxic metals like aluminum (Al3+) and manganese (Mn), which become highly soluble below pH 5.5, posing significant threats to plant health (Warke et al., 2024). These imbalances lead to nutrient deficiencies and toxicities, reducing crop yields and potentially impacting human health as toxic elements can enter the food chain. Soil pH critically influences microbial activity and diversity, with most beneficial microorganisms thriving between pH 6.0 and 7.5. Acidification reduces these populations, impairing organic matter decomposition and nitrogen fixation. While acidophilic fungi may increase, their efficiency in breaking down organic molecules is lower, slowing nutrient cycling (Farooqi et al., 2024). Microorganisms are vital for phosphorus activation, even in P-deficient acidic soils, though this becomes more challenging with increasing stand age due to reduced microbial biomass and acid phosphatase activity (Li et al., 2024). The most immediate consequence of soil acidity and associated aluminum toxicity is the rapid inhibition of root elongation and overall root development. Aluminum toxicity impedes cell division and elongation in root tips, leading to root damage, stunted growth, and a characteristic "stubbly" appearance (Warke et al., 2024; Li et al., 2024). This directly compromises the plant's ability to absorb water and nutrients, especially immobile ones like phosphorus, rendering plants highly vulnerable to drought and nutritional shortages (Khaled and Sayed, 2023). Manganese toxicity also contributes to root damage and impaired nutrient uptake (Warke et al., 2024). Aluminum toxicity directly impairs the integrity and function of root cell membranes. Aluminum ions can adhere to the phospholipid bilayer of the plasma membrane, destabilizing the membrane potential and inhibiting the activity of H+-adenosine triphosphatase (H+-ATPase), an enzyme crucial for proton removal and ion transport (Li et al., 2024; Yan et al., 2024). Soil acidity also demonstrably reduces the nutrient absorption capacity of plants, with studies showing decreased total nitrogen, phosphorus, and potassium content in crops like eggplant at lower pH levels (Yan et al., 2024). The impact of soil acidity is not merely a nutrient shortage in the soil, but a direct assault on the plant's cellular machinery responsible for acquiring nutrients. This leads to a systemic plant failure, where even if nutrients are present in the soil, the plant cannot effectively absorb them, resulting in reduced biomass and yield. The cumulative effects of nutrient deficiencies, metal toxicities, and impaired nutrient uptake mechanisms ultimately lead to significant reductions in plant growth, vigor, and agricultural yield (Warke et al., 2024; Khaled and Sayed, 2023; Li et al., 2024). Plants growing in acidic conditions often exhibit symptoms such as stunted growth, chlorosis

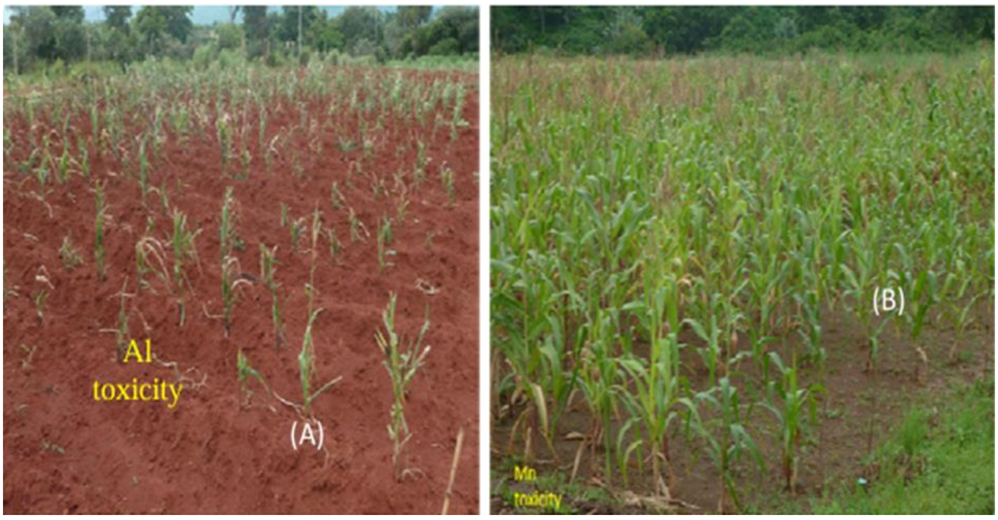

Figure 1
Impact of aluminum toxicity (A) and manganese toxicity (B) on maize plants (65 days after planting) in the fields at Ebolowa and Nkolbisson, respectively. Source: (Tekeu et al., 2015)

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Figure 2
Mechanized application of lime.
Source: (O'Connor & Parsons, 2006)

(yellowing of leaves), poor legume nodulation, and abnormal leaf colors. Different crops exhibit varying sensitivities to acidic soils, with optimal pH ranges for popular field crops typically between 6.0 and 7.0 (Warke et al., 2024). Despite progress in understanding soil acidification, significant research gaps remain, particularly regarding its long-term effects on soil properties, nutrient dynamics, and microbial communities. Current studies often overlook the complex interacttions in the rhizosphere and the variability of acidification impacts across different crops and environments. Additionally, the effectiveness and sustainability of remediation practices such as liming and organic amendments need more comprehensive evaluation under diverse soil conditions. Addressing these gaps requires integrated, multidisciplinary research that spans molecular to ecosystem scales to develop effect-tive, sustainable strategies for managing soil acidity in agricultural systems (Warke et al., 2024; Khaled and Sayed, 2023; Li et al., 2024; Lehmann et al., 2020; Li et al., 2024). This review aims to provide a thorough understanding of soil acidity and its complex effects on agricultural ecosystems in Ethiopia and Sub-Saharan Africa. It focuses on examining the natural and human-induced causes of soil acidification, their impact on soil properties and microbial communities, and how acidic conditions influence nutrient availability and toxic metal mobility. Additionally, the review explores the mechanisms by which soil acidity, especially aluminum toxicity, hinders nutrient uptake at the plant physiological level. Finally, it highlights critical research gaps and suggests directions for sustainable management. strategies to improve soil health and crop productivity in the region

Literature review

Causes and mechanisms of soil acidity

Natural factors influencing soil acidity. Soil acidity can originate from several natural processes including parent material weathering, organic matter decomposition, and high rainfall causing leaching of basic cations. Parent rock types rich in quartz and poor in base cations often give rise to acidic soils, particularly in regions with intense weathering such as the Ethiopian Highlands (Warke et al., 2024). Organic matter decomposition produces organic acids that contribute to acidity by releasing hydrogen ions (H+) into the soil solution (Farooqi et al., 2024). Furthermore, high precipitation rates in humid tropical climates lead to leaching of calcium (Ca2+), magnesium (Mg2+), and potassium (K+), thereby reducing soil buffering capacity and increasing acidity (Tully et al., 2015).

Anthropogenic drivers of soil acidification. Human activities, especially agricultural practices, greatly accelerate soil acidification beyond natural rates. Continuous use of ammonium-based fertilizers (such as urea and ammonium sulfate) leads to acidification through nitrifycation, a microbial process that produces hydrogen ions (H+) (Arnall, 2024). Crop removal of basic cations without adequate replenishment further depletes soil bases, while acid rain primarily from industrial emissions intensifies cation leaching (Farooqi et al., 2024; Khan et al., 2025). In Sub-Saharan Africa, expanding cultivation on marginal lands with poor nutrient management practices has exacerbated acidification trends, notably in smallholder farming systems with limited access to lime and organic amendments (Tully et al., 2015; Warke et al., 2024).

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Soil acidification processes and dynamics. Soil acidification is a gradual process involving chemical, biological, and physical interactions that alter soil properties. Key mechanisms include the replacement of basic cations by hydrogen (H+) and aluminum (Al3+) ions on soil exchange sites, resulting in lower pH and increased solubility of toxic metals such as Al and Mn (Li et al., 2024). The increased concentration of Al3+ in acidic soils is phytotoxic, impairing root growth and nutrient uptake (Yan et al., 2024). Biological processes, including microbial activity shifts, are influenced by acidification, reducing decomposition rates and nutrient cycling efficiency (Farooqi et al., 2024). Over time, these changes lead to reduced soil fertility and crop productivity, particularly when soil amendments are not applied to counteract acidity (Khaled and Sayed, 2023). A conceptual overview of the soil acidifycation process is shown in Figure 3.

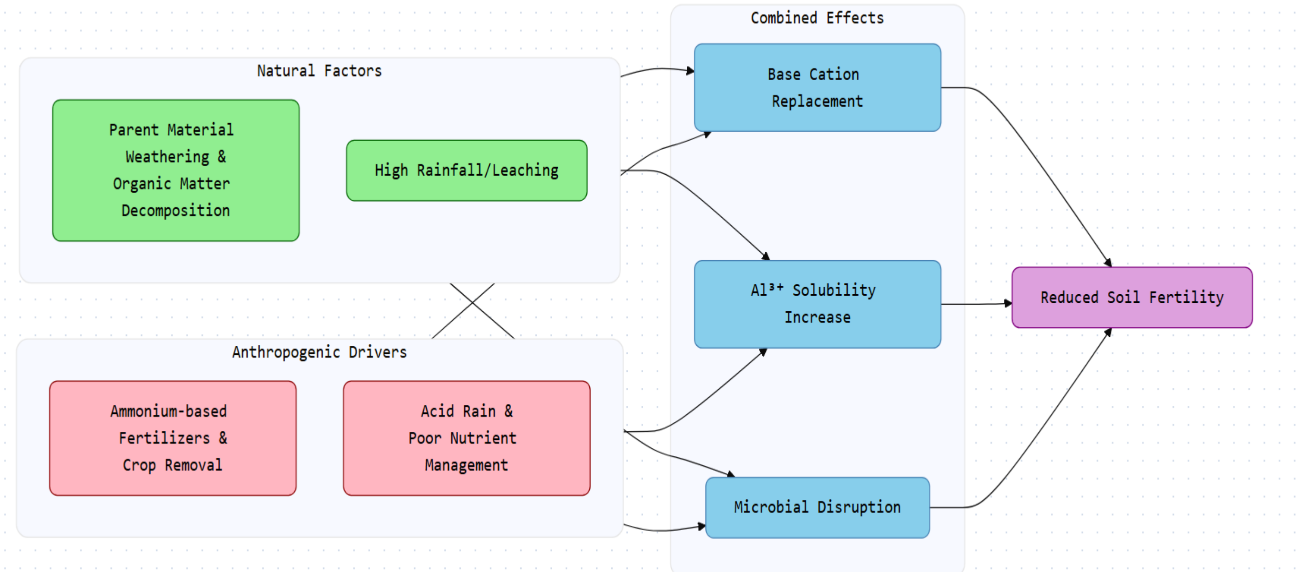

Figure 3. *Integrated mechanisms of soil acidification. Adapted from Farooqi et al., 2024; Arnall, 2024; Tully et al., 2015; Warke et al., 2024; and Khan et al., 2025)*

Effects of soil acidity on soil chemical properties and nutrient dynamics

In this review, nutrient dynamics refer to the processes governing nutrient transformation, fixation, leaching, and biological cycling in soils under acidic conditions, rather than nutrient concentrations or availability alone.

Impact on soil pH and exchangeable cations. Soil acidity is primarily characterized by low pH, which directly influences the concentration and availability of essential exchangeable cations such as calcium (Ca2+), magnesium (Mg2+), potassium (K+), and sodium (Na+). As pH declines, these basic cations are progressively displaced by hydrogen (H+) and aluminum (Al3+) ions on soil exchange sites, leading to nutrient depletion and impaired soil fertility (Kochian et al., 2015; Warke et al., 2024). This cation exchange imbalance adversely affects soil structure and plant nutrient uptake, resulting in reduced crop productivity (Farooqi et al., 2024).

Aluminum and manganese toxicity. At pH levels below 5.5, aluminum becomes more soluble and toxic to plants. Aluminum toxicity inhibits root growth by damaging root tips, interfering with cell division, and altering nutrient and water uptake mechanisms (Kochian et al., 2015; Yan et al., 2024). Manganese (Mn) toxicity can also arise in acidic soils, although its effects are less well understood. Both metals can cause physiological stress and reduce plant vigor, further limiting agricultural yields (Farooqi et al., 2024; Warke et al., 2024).

Nutrient availability, fixation, and leaching. Soil acidity alters nutrient dynamics by affecting nutrient fixation, solubility, transformation, and leaching processes. In acidic soils, phosphorus dynamics are strongly constrained by increased fixation through reactions with iron and aluminum oxides, which substantially reduce the plant-available phosphorus pool (Tully et al., 2015; Li et al., 2024). At the same time, soil acidification enhances the solubility of certain micronutrients such as iron (Fe) and zinc (Zn), which may accumulate to toxic concentrations and disrupt plant physiological processes (Farooqi et al., 2024). Acidic conditions also

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accelerate nutrient leaching, particularly of nitrate and base cations such as potassium, calcium, and magnesium, due to reduced cation exchange capacity and weaker nutrient retention on soil colloids. These leaching losses not only diminish soil fertility but also intensify environmental contamination of groundwater and surface waters (Mosier et al., 2021).

Soil buffering capacity and liming potential. Soil buffering capacity refers to the soil's ability to resist pH changes. Soils rich in calcium carbonate or with high cation exchange capacity exhibit greater buffering, slowing acidification processes (Khaled and Sayed, 2023). Liming is a common practice to neutralize soil acidity by supplying calcium carbonate or other alkaline materials. Its effectiveness depends on soil texture, acidity degree, and lime quality (Warke et al., 2024). However, the sustainability of liming in Sub-Saharan Africa is challenged by cost, availability, and application practices (Tully et al., 2015).

Effects of soil acidity on soil physical properties

Soil structure and aggregate stability. Soil acidity adversely affects soil structure by altering the stability of soil aggregates. Acidic conditions often reduce the activity of soil microorganisms and decrease the production of organic binding agents such as polysaccharides, which are critical for aggregate formation and stability (Six et al., 2004; Warke et al., 2024). The loss of exchangeable base cations under low pH can weaken particle bonding, leading to the breakdown of aggregates and increased soil dispersion; however, the abundance of other cations, particularly Fe^{3+} and Al^{3+}, can promote aggregation and partially offset this effect (Zhao et al., 2017). Poor aggregate stability diminishes soil aeration and root penetration, ultimately reducing soil fertility and crop productivity (Farooqi et al., 2024).

Soil porosity, bulk density, and water retention. Soil acidity influences porosity and bulk density by promoting soil particle dispersion and compaction. Acidic soils with reduced aggregate stability tend to have decreased macroporosity, leading to higher bulk density and poorer water infiltration rates (Khaled & Sayed, 2023). Consequently, water retention capacity may decline due to compaction and reduced pore connectivity, affecting plant available water and increasing susceptibility to drought stress (Tully et al., 2015). These physical changes can exacerbate crop water stress and reduce yields, especially in regions like the Ethiopian Highlands where acidic soils prevail.

Influence on soil erosion and compaction. Soil acidity can indirectly enhance soil erosion risk by weakening soil structure and reducing vegetative cover through poor crop growth caused by acid toxicity (Warke et al., 2024). The breakdown of soil aggregates and increased surface crusting encourage runoff and topsoil loss (Six et al., 2004). Furthermore, acidic conditions can lead to soil compaction, which decreases infiltration and increases surface runoff, further accelerating erosion processes (Zhang et al., 2025). This erosion not only depletes fertile topsoil but also exacerbates the cycle of soil degradation common in Sub-Saharan Africa's agricultural landscapes (Tully et al., 2015).

Influence of soil acidity on soil biological properties

Microbial community composition and activity. Soil acidity profoundly affects microbial community composition and overall activity. Acidic conditions typically reduce bacterial diversity and biomass, favoring acidophilic fungi and certain archaea, which are less efficient in nutrient cycling (Rousk et al., 2010; Li et al., 2024). This shift leads to an imbalance in microbial populations that perform essential processes such as nitrogen mineralization and organic matter decomposition. Reduced microbial activity under low pH limits key soil processes, impeding nutrient availability and overall soil fertility (Farooqi et al., 2024). Moreover, acidification can inhibit enzymatic functions critical to the soil microbiome's role in sustaining healthy agroecosystems, thus weakening the soil's resilience to environmental stress.

Nitrogen fixation and symbiotic relationships. Soil acidification negatively impacts biological nitrogen fixation by impairing the survival and efficiency of rhizobia bacteria involved in legume symbiosis (Bashan and de-Bashan, 2010). Low pH conditions reduce nodulation and nitrogenase enzyme activity, thereby limiting nitrogen inputs from biological sources critical for sustainable agriculture (Warke et al., 2024). Additionally, the altered soil chemistry can hinder mycorrhizal associations, which are essential for phosphorus uptake and improved nutrient use efficiency in many crops (Smith and Read, 2010). The disruption of these symbiotic relationships can result in lower plant growth rates and yield, further exacerbating the challenges posed by acidic soils in vulnerable agricultural regions.

Soil fauna diversity and functionality. Soil fauna such as earthworms, nematodes, and arthropods are sensitive to acidic conditions. Acidification can decrea-

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se earthworm abundance and diversity, reducing soil bioturbation, aeration, and organic matter mixing, which are crucial for maintaining soil structure and nutrient cycling (Edwards and Bohlen, 1996). Declines in soil fauna disrupt trophic interactions and nutrient cycling, weakening the soil food web and ecosystem resilience (Lavelle et al., 2000). These biological losses not only reduce soil fertility but also increase vulnerability to soil erosion and compaction, negatively impacting crop productivity and long-term soil health.

Impact on soil organic matter decomposition. Soil acidity slows organic matter decomposition by suppressing microbial enzymes and decomposer populations (Farooqi et al., 2024; Rousk et al., 2010). Acidic environments reduce activities of key enzymes such as cellulase, ligninase, and phosphatase, which are critical for breaking down plant residues and releasing nutrients in bioavailable forms (Li et al., 2024). As a result, nutrient mineralization rates decrease, limiting nutrient availability for crops and reducing soil fertility over time (Lehmann et al., 2020). The slower decomposition also leads to accumulation of partially decomposed organic material, which can alter soil physical properties and further impede nutrient cycling processes essential for sustainable agricultural productivity.

Soil acidity and the holistic concept of soil health

The impacts of soil acidity extend beyond individual chemical, physical, and biological properties to collectively degrade overall soil health, a concept encompassing the continuous capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans (Lehmann et al., 2020). Acidification fundamentally compromises this capacity by creating an environment where nutrient cycling is impaired, beneficial microbial communities are diminished, and physical stability is reduced. For instance, the combined effects of aluminum and manganese toxicity, nutrient imbalances, and reduced organic matter decomposition directly limit the soil's ability to support vigorous plant growth and maintain its ecological functions. A healthy soil should exhibit robust buffering capacity, efficient nutrient retention, and thriving biodiversity all of which are severely undermined by persistent acidity. Addressing soil acidity is therefore not merely about correcting pH, but about restoring the interconnected functions that define a healthy, resilient soil ecosystem capable of contributing to long-term agricultural sustainability and environmental well-being. This holistic perspective emphasizes the need for integrated management strategies that consider all facets of soil health.

Impact of soil acidity on crop nutrient uptake and health

Nutrient uptake mechanisms under acidic conditions. Soil acidity profoundly influences the physiological and biochemical pathways involved in nutrient uptake by plants. Acidic conditions increase the solubility of toxic metals such as aluminum (Al^{3+}) and manganese (Mn), which bind to root cell membranes and cause physical and chemical damage that impairs membrane integrity and disrupts active transport processes (Yan et al., 2024; Li et al., 2024). This damage inhibits the function of H^+-adenosine triphosphatase (H^+-ATPase), an enzyme crucial for maintaining proton gradients that drive nutrient uptake. Simultaneously, soil acidity disrupts nutrient dynamics by enhancing phosphorus fixation and reducing the mobility of base cations such as calcium and magnesium through precipitation and adsorption reactions, resulting in nutrient imbalances that impair metabolic functions within the plant (Warke et al., 2024). The combined effects of toxic metal interference and disrupted nutrient dynamics severely limit nutrient acquisition, even when total soil nutrient pools are sufficient, thereby compromising crop health and yield.

Root growth and development constraints. Root systems are particularly vulnerable to soil acidity, with aluminum toxicity recognized as one of the most detrimental effects on root development. Aluminum ions inhibit root elongation by damaging the root apical meristem, where cell division and elongation occur, resulting in stunted and thickened root systems with reduced surface area (Khaled and Sayed, 2023; Warke et al., 2024). These damaged roots exhibit a "stubby" morphology, which severely restricts the plant’s ability to explore soil for water and nutrients. Additionally, manganese toxicity exacerbates root damage by inducing oxidative stress, disrupting membrane integrity, and impairing nutrient transporter proteins (Li et al., 2024). Impaired root development limits symbiotic relationships such as mycorrhizal associations and nitrogen-fixing nodules, further restricting nutrient access and biological nitrogen fixation, essential for legume growth in acidic soils. These physiological impairments in roots significantly contribute to reduced water uptake and drought susceptibility, affecting overall plant vigor. The visual symptoms of aluminum and manganese toxicity in maize are shown in Figure. 1.

Effects on crop physiological processes. Beyond root development, soil acidity adversely affects nume-

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rous physiological processes essential for maintaining crop health. Nutrient imbalances induced by acidic conditions interfere with chlorophyll synthesis and function, leading to symptoms such as chlorosis, reduced photosynthetic efficiency, and lower biomass accumulation (Farooqi et al., 2024). Acidic soils also induce oxidative stress by increasing the production of reactive oxygen species (ROS), which damage cellular components including membranes, proteins, and DNA, thereby impairing enzymatic activity and cellular metabolism (Yan et al., 2024). Disruption of metabolic homeostasis further limits nutrient assimilation and internal transport, reducing the plant's capacity to utilize absorbed nutrients effectively. Additionally, acid stress can alter hormonal regulation, including auxins and cytokinins, which control growth and development, thereby intensifying growth inhibition and weakening the plant's resilience to environmental stress.

Crop yield and quality responses to soil acidity. The cumulative physiological, biochemical, and root-level impairments associated with soil acidity ultimately result in substantial declines in crop yield and quality. Acid-sensitive crops commonly exhibit reductions in shoot and root biomass, grain weight, and nutrient density, negatively affecting both the quantity and nutritional value of harvested products (Warke et al., 2024; Khaled and Sayed, 2023). In addition, the accumulation of toxic metals such as aluminum in edible plant tissues poses potential health risks to consumers through bioaccumulation within the food chain (Farooqi et al., 2024). Crop quality traits, including protein concentration, vitamin content, and sensory attributes, may also be adversely affected under acidic soil conditions. In resource-limited farming systems where corrective amendments such as lime are inadequately applied, these negative effects are often intensified, highlighting the importance of integrated soil acidity management strategies.

Variation in crop tolerance to soil acidity. Crop species and cultivars differ markedly in their tolerance to acidic soils and associated metal toxicities. Crops such as rye, oats, and barley generally exhibit greater tolerance to low pH and aluminum toxicity due to adaptive traits including thicker root cell walls, enhanced exclusion or detoxification mechanisms, and efficient internal nutrient regulation (Warke et al., 2024). In contrast, key staple crops such as common bean, maize, and many legumes are more sensitive and often experience substantial yield reductions under acidic conditions. This variability underscores the importance of selecting and deploying acid-tolerant varieties adapted to local soil conditions to sustain crop health and yield. Contemporary breeding programs increasingly incorporate genetic markers for acid tolerance, including traits associated with improved root growth, organic acid exudation that chelates toxic metals, and enhanced nutrient use efficiency (Kopittke et al., 2024). These advances provide promising pathways for mitigating the impacts of soil acidity and strengthening food security in acid-affected regions.

Agronomic management strategies to mitigate soil acidity and enhance productivity

Liming: types, application methods, and efficiency. Liming remains the cornerstone of soil acidity management worldwide due to its effectiveness in neutralizing soil acidity and replenishing base cations essential for crop growth (Enesi et al., 2023). Various types of lime including calcitic lime (mainly calcium carbonate), dolomitic lime (calcium magnesium carbonate), and industrial by-products like slag differ in their chemical composition, neutralizing value, and cost, which affect their suitability for specific soils and crop systems (Farooqi et al., 2024). Application methods vary, with broadcast liming being the most common due to ease, but incorporation into the soil often improves reaction rates and effectiveness. Banding lime near plant roots can also enhance local pH adjustment. The efficiency of liming depends on soil texture, moisture availability, organic matter content, and the initial soil pH; finer particle lime reacts faster but may be more expensive (Warke et al., 2024). Despite its benefits, liming may not be accessible to many smallholder farmers in developing countries due to cost and availability challenges, emphasizing the need for optimizing lime application rates and timing to maximize agronomic benefits while minimizing environmental impacts. Additionally, liming can have secondary benefits such as improving soil microbial activity and nutrient availability, further enhancing crop productivity. Mechanized lime application is illustrated in Figure 2. A summary of common liming materials, their chemical composition, and application considerations is presented in Table 1 and regional data on lime application rates and effects in Sub-Saharan Africa are presented in Table 2.

Integrated nutrient management approaches. Integrated Nutrient Management (INM) involves the strategic combination of chemical fertilizers, organic amendments, and biological nutrient sources to maintain soil fertility while reducing the risk of further

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Table 1. *Common liming materials, their chemical composition, neutralizing value, and typical application considerations for soil acidity management.*

Liming material	Chemical composition	Neutralizing Value (NV)	Application considerations	Sources
Calcitic Lime	Primarily $CaCO_3$	~90-100% $CaCO_3$ equivalent	Most common, readily available, increases Ca	Farooqi et al., 2024
Dolomitic Lime	$CaCO_3$ + $MgCO_3$	~90-108% $CaCO_3$ equivalent	Provides Ca and Mg, good for Mg-deficient soils	Warke et al., 2024
Quicklime (CaO)	Calcium oxide	~150-170% $CaCO_3$ equivalent	Faster reaction, caustic, requires careful handling	Enesi et al., 2023
Hydrated Lime ($Ca(OH)_2$)	Calcium hydroxide	~120-135% $CaCO_3$ equivalent	Faster reaction, fine particles, caustic	Enesi et al., 2023
Basic Slag	By-product of steel industry	Variable, typically 50-70% $CaCO_3$ equivalent	Provides Ca, Mg, P, Si, good for micro-nutrient supply	Farooqi et al., 2024

Table 2. *Summary of lime types, application rates, methods, and effects on soil pH in selected Sub-Saharan African countries*

Country	Type of Lime	Rate of Lime (t/ha)	Application method	Effect on pH	Sources
Ethiopia	$CaCO_3$	0.06–14	Soil surface (microdosing), incorporation, soil surface (broadcasting)	Increased pH	Alemu et al., 2022
Ethiopia	$CaCO_3$	3.6–7.2	Incorporation	NA	Fekadu et al., 2018
Ethiopia	$CaCO_3$	2.9–7.5	Incorporation	Increased pH	Lulu et al., 2022
Nigeria	Gypsum, Ag lime, Agricultural lime + Gypsum	2.5–7.5	Incorporation	Increased pH	Anikwe et al., 2016
Nigeria	$CaCO_3$	2–20	Incorporation	Increased pH	Adeoye and Singh, 1985

acidification. INM promotes nutrient use efficiency and supports soil health by balancing nutrient inputs with crop demands, thus reducing nutrient losses through leaching or volatilization, which are common problems in acidic soils (Li et al., 2024). Incorporation of nitrogen-fixing legumes into crop rotations enriches soil nitrogen naturally, reduces dependence on ammonium-based fertilizers, and improves soil organic carbon stocks, all of which contribute to buffering soil pH (Kopittke et al., 2024). Organic inputs such as manure or compost enhance soil structure and microbial diversity, which supports nutrient cycling and stabilizes soil chemical properties. The success of INM depends on site-specific soil testing, crop type, and farmer knowledge, which necessitates extension services and capacity building. INM is especially relevant in Sub-Saharan Africa and Ethiopian highlands, where smallholder farmers often rely heavily on inorganic fertilizers, which can exacerbate soil acidification without complementary organic matter inputs.

Use of organic amendments and biochar. The application of organic amendments such as compost, animal manure, and biochar plays a dual role in mitigating soil acidity by increasing soil organic matter and improving soil chemical and physical properties. Organic amendments contribute alkaline substances that help neutralize acidity, enhance cation exchange capacity, and improve soil buffering capacity (Farooqi et al., 2024). Biochar, a stable carbon-rich product obtained from pyrolysis of biomass, has received growing attention for its ability to increase soil pH and reduce aluminum toxicity in acid soils (Jemal and Yakob, 2021). Beyond chemical benefits, biochar improves soil structure, water retention, and microbial habitat, which together enhance nutrient retention and availability. However, the quality of organic amendments varies widely depending on feedstock and production methods, influencing their liming potential and nutrient content. Challenges for widespread adoption include cost, availability, and farmer awareness, but emerging research suggests that integrating biochar with traditionnal organic amendments could provide a sustainable and cost-effective strategy for soil acidity management in resource-limited environments (Tadesse, 2024).

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Table 3: *A comparison of the relative tolerance of common agricultural crops to soil acidity and aluminum toxicity, including their optimal pH ranges or tolerance classifications, relevant to Ethiopia and Sub-Saharan Africa.*

Crop	Tolerance to Acidity	Optimal pH range	Key Mechanisms of Tolerance (if applicable)	Sources
Maize (Corn)	Sensitive to Moderately Sensitive	6.0-7.0	Some varieties show improved Al exclusion/detoxification	(Warke et al., 2024; Kopittke et al., 2024)
Wheat	Moderately Sensitive to Tolerant	6.0-7.0	Varies by cultivar, some exhibit Al tolerance	(Warke et al., 2024)
Barley	Tolerant	6.0-7.0	Generally, more tolerant to acidity than wheat or maize	(Warke et al., 2024)
Common Bean (Legume)	Sensitive	6.0-7.5	Highly sensitive to Al toxicity, impaired nodulation	(Warke et al., 2024)
Teff (Ethiopian staple)	Moderately Tolerant	5.0-7.0	Important for acidic regions in Ethiopia	(Tadesse, 2024)
Rye	Highly Tolerant	5.0-7.0	Known for strong acid tolerance	(Warke et al., 2024)
Oats	Highly Tolerant	5.0-7.0	Robust growth in acidic conditions	(Warke et al., 2024)

Adoption of acid-tolerant crop varieties. The development and adoption of acid-tolerant crop varieties represent a critical long-term strategy for maintaining productivity on acidic soils. These varieties possess genetic traits that enable them to tolerate aluminum and manganese toxicity, maintain root elongation in low pH conditions, and efficiently uptake nutrients even when availability is limited by soil chemistry (Kopittke et al., 2024). Advances in plant breeding, including marker-assisted selection and genetic engineering, have facilitated the development of varieties of major staple crops like maize, wheat, barley, and legumes that can thrive in acidic environments (Warke et al., 2024). Use of acid-tolerant crops reduces the dependency on costly soil amendments and lime, making it especially beneficial for smallholder farmers in Ethiopia and other Sub-Saharan countries where soil acidity is widespread. Furthermore, these varieties contribute to greater yield stability under acid stress, which is crucial for food security in vulnerable regions affected by soil degradation. A comparison of crop acid tolerance and optimal pH ranges is provided in Table 3.

Soil and water conservation practices. Soil and water conservation practices are vital for preventing the worsening of soil acidity by protecting soil from erosion, nutrient loss, and organic matter depletion. Techniques such as contour plowing, terracing, cover cropping, and reduced or conservation tillage help maintain soil structure and organic matter, which are critical factors in buffering soil pH and reducing acidification (Farooqi et al., 2024). These practices also improve water infiltration and retention, which minimizes nutrient leaching and maintains a more stable soil chemical environment. In the Ethiopian highlands and similar landscapes with steep slopes and high rainfall, conservation measures help protect fragile soils from degradation and preserve their productive capacity (Warke et al., 2024). Adoption of such practices requires farmer awareness, technical support, and sometimes policy incentives to encourage widespread implementation.

Emerging and advanced technologies for soil acidity mitigation. Recent technological innovations are revolutionizing the approach to soil acidity management by enabling more precise, effective, and sustainable interventions. Precision soil amendments use GPS and soil acidity mapping to apply lime and other amendments variably across a field based on local soil conditions, improving efficiency and reducing waste (Khaled & Sayed, 2023). Biotechnology approaches, including the use of acid-tolerant microbial inoculants, aim to enhance nutrient cycling and reduce toxic metal bioavailability by promoting beneficial microbial communities (Li et al., 2024). Remote sensing technologies, such as satellite imagery and drones equipped with sensors, facilitate large-scale soil acidity mapping and monitoring, allowing for timely decision-making and intervention planning (Yan et al., 2024). Additionally, nanotechnology offers potential for developing novel soil amendments that improve nutrient delivery and soil conditioning at the molecular level, although this remains in early research stages.

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These technologies, while promising, require validation under diverse field conditions and must be accessible to resource-poor farmers to achieve large-scale impact.

Case studies and research advances in Ethiopia and Sub-Saharan Africa

Soil acidity status and mapping in Ethiopia. Soil acidity has been extensively mapped in Ethiopia, particularly in the highland regions where acidic soils affect nearly 43% of arable land (Warke et al., 2024; Tadesse, 2024). Regional assessments using geospatial tools have highlighted widespread areas of pH below 5.5, particularly in Oromia, SNNP, and Amhara regions, where continuous cultivation, high rainfall, and poor soil management exacerbate acidification (Tadesse, 2024). Digital soil mapping initiatives by the Ethiopian Ministry of Agriculture and partners like the Ethiopian Soil Information System (EthioSIS) have produced national pH maps, providing critical decision-making tools for lime recommendations and site-specific soil management (Tadesse, 2024).

Impact of liming and nutrient management on crop yields. Several case studies in Ethiopia and other Sub-Saharan African countries confirm that lime application significantly improves crop yields. In central Ethiopia, lime application combined with phosphorus fertilizer increased wheat yield by up to 80% compared to control plots (Enesi et al., 2023; Tadesse, 2024). A meta-analysis by Enesi et al. (2023) across African agro-ecologies showed that liming raised crop productivity by improving soil pH, enhancing nutrient uptake, and mitigating aluminum toxicity. Similarly, integrated soil fertility management approaches combining lime, manure, and mineral fertilizers are proving effective in acidic soils of Kenya and Uganda, leading to improved maize and bean productivity (Sanginga and Woomer, 2009). Table 4 summarizes case studies on lime application and yield responses in Ethiopia and Sub-Saharan Africa.

Table 4. *A summary of selected case studies from Ethiopia and Sub-Saharan Africa, detailing the impact of liming and/or integrated nutrient management on specific crop yields, along with the reported percentage increase or key findings.*

Case Study Location (Region/Country)	Intervention(s)	Crop(s)	Key Findings/Yield Increase	Sources
Central Ethiopia	Lime + Phosphorus fertilizer	Wheat	Yield increases up to 80%	Enesi et al., 2023; Tadesse, 2024
Various African Agro-ecologies (Meta-analysis)	Liming	Various crops	Increased crop productivity by improving soil pH, nutrient uptake, Al toxicity mitigation	Enesi et al., 2023
Kenya and Uganda	Lime + Manure + Mineral fertilizers (INM)	Maize, Common Bean	Improved productivity in acidic soils	Sanginga and Woomer, 2009
Southern Ethiopia (e.g., Wolaita Zone)	Lime application	Maize	Significant yield response observed, demonstrating local effectiveness	Warke et al., 2024

Significant research advances on soil acidity and agronomic impacts in Ethiopia and Sub-Saharan Africa. Research over the past decade has advanced our understanding of soil acidity's physiological and agronomic impacts. In Ethiopia, studies have demonstrated how aluminum toxicity impairs root elongation, leading to poor nutrient uptake in crops like barley and wheat (Tadesse, 2024). Innovations in liming technologies, including microdosing and localized placement, have been developed to improve lime-use efficiency and reduce cost barriers. Furthermore, biochar derived from crop residues has shown promise in buffering soil pH and enhancing microbial activity in acidified soils (Jemal and Yakob, 2021). These findings highlight the need for adaptive, low-cost technologies that can be integrated into smallholder farming systems in acid-affected regions of Sub-Saharan Africa.

Socioeconomic and extension challenges. Despite technical advances, farmers in Ethiopia and Sub-Saharan Africa face significant socioeconomic and institutional barriers to managing soil acidity. Key challenges include the high cost and limited availability of lime, weak extension services, and lack of awareness about the causes and effects of soil acidification (Tadesse, 2024). Many smallholders are constrained by land tenure insecurity and low investment capacity, making long-term soil health management difficult. Additionally, national policies often prioritize short-term yield gains

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over long-term soil restoration, hindering widespread adoption of soil acidity management practices. Strengthening farmer training, market access, and public-private partnerships will be critical to overcoming these barriers.

Future research directions and policy implications

Development of cost-effective soil acidity amendments. Future research should focus on developing low-cost and locally available soil amendments to mitigate soil acidity sustainably. While agricultural lime remains the primary solution, its high cost and transportation limitations hinder widespread use in rural Ethiopia and Sub-Saharan Africa (Tadesse, 2024). Researchers are exploring alternative amendments such as biochar, gypsum, and compost, which not only raise soil pH but also enhance nutrient retention and microbial activity (Jemal and Yakob, 2021). Improved formulations of pelletized lime, microdosing techniques, and use of industrial by-products like sugarcane filter cake and paper sludge also warrant investigation for their cost-efficiency and agronomic benefits (Enesi et al., 2023).

Breeding and biotechnology for acid tolerance. Breeding programs and biotechnology must prioritize the development of crop varieties tolerant to acidic soils and aluminum toxicity. Root traits associated with organic acid exudation (e.g., citrate and malate) help in detoxifying aluminum ions, thereby enhancing nutrient uptake and root growth (Kochian et al., 2015). Genomic-assisted breeding and CRISPR gene editing techniques offer powerful tools to identify and introduce acid-tolerance genes into major cereal crops such as maize, wheat, and teff. Incorporating these traits into national breeding programs can accelerate the development of cultivars that thrive in acid-affected soils, particularly in Sub-Saharan farming systems.

Climate change interactions with soil acidity. Climate change is expected to intensify soil acidity problems due to increased rainfall variability, leaching, and organic matter decomposition. Rising temperatures and erratic precipitation may accelerate the release of hydrogen ions and nutrient loss through leaching, worsening acidification, especially in highland areas (Tully et al., 2015). Future research should investigate the synergistic effects of climate change and soil acidification on soil carbon sequestration, nutrient dynamics, and microbial balance. Adaptive soil management strategies must integrate climate resilience into acidity mitigation to safeguard long-term soil health and food security.

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Extension and farmer adoption strategies. Effective policy and extension strategies are crucial to ensure widespread adoption of soil acidity mitigation practices. Current gaps in knowledge transfer, weak institutional capacity, and limited access to lime products have slowed the implementation of recommendations at the farm level (Tadesse, 2024). Future programs should incorporate participatory extension models, use of digital tools for site-specific lime recommendation, and capacity-building of rural extension agents. Policy support is also needed to subsidize lime inputs, incentivize private sector lime production, and include soil acidity mitigation in national soil health strategies and agricultural investment plans.

Conclusions

Soil acidity is a widespread constraint to crop production in Ethiopia and Sub-Saharan Africa, significantly reducing soil fertility and crop yields. This review summarized key causes and the detrimental effects of acid soils on soil properties and plant growth. It also explored a range of effective agronomic management strategies, including liming, integrated nutrient manage-ment, organic amendments like biochar, and the use of acid-tolerant crop varieties. Soil and water conservation practices and emerging technologies such as precision liming and microbial inoculants offer promising tools to enhance soil health sustainably. Regional case studies confirm that targeted interventions can substantially improve productivity in acid-affected areas. However, socioeconomic and institutional challenges such as high lime costs and weak extension services limit adoption by smallholder farmers. Moving forward, research must focus on developing affordable amendments, breeding acid-tolerant crops, and strengthening extension and policy support to enable widespread, sustainable management of soil acidity and improve food security under changing climate conditions.

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