

Acidic soil amelioration strategies for improving soil fertility: a systematic literature review of techniques, materials, and mechanisms

Ezra Delfianza^{1*}, Fitri Khoerunnisa²

¹Department of Chemistry Education, Faculty of Mathematic and Natural Science Education, Universitas Pendidikan Indonesia, Bandung 40154, West Java, Indonesia

²Department of Chemistry, Universitas Pendidikan Indonesia. Jl. Dr. Setiabudi No.229, Bandung 40154, West Java, Indonesia

^{*}Email address: ezradelfianza@upi.edu

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ABSTRACT

Declining agricultural productivity in tropical and subtropical regions is largely due to high soil acidity, which inhibits nutrient availability and increases the solubility of toxic elements such as aluminum and iron. Acidic soil is one of the main constraints in agricultural systems, characterized by low soil pH and an imbalance of essential nutrients for plants. This study aimed to systematically review various approaches to acid soil amelioration, focusing on the mechanisms and materials used. The method used in this study was a Systematic Literature Review (SLR), through an analysis of 38 reputable scientific articles published between 2021 until 2025 and indexed in the Scopus database. The article selection process was based on inclusion criteria specifically related to the results of acidic soil amelioration research. The synthesis results show that acidic soil amelioration approaches could be grouped into several main categories, namely liming-based, biochar-based, biochar and organic-based, organic (non-biochar)-based, organomineral-based, and industrial waste-based. Although research on acid soil amelioration has developed rapidly, there was still considerable variation in the selection of materials, composition, and application methods used. Overall, this systematic literature review provides a structured overview of the mechanisms and materials used in acid soil amelioration.

Keywords: acidic soil, soil amelioration, soil fertility, soil modifier, soil sustainability

INTRODUCTION

Soil fertility is a fundamental issue in the Soil fertility is a fundamental issue in the sustainability of global agricultural systems, especially in areas experiencing land degradation due to environmental pressures and intensive agricultural activities (X. Zhu et al., 2024; Žurovec et al., 2021). It determines the soil's ability to supply nutrients, sustain biological activity, and support crop growth, thereby directly influencing agricultural productivity and food system stability (Bossolani et al., 2021; W. Zhu et al., 2025; Žurovec et al., 2021). Declining soil quality has been widely linked to reduced crop productivity, particularly in tropical agricultural lands, where one of the most dominant degradation processes is soil acidification occurring naturally or accelerated

by anthropogenic activities (Peñalver-Alcalá et al., 2021; Jouichat et al., 2024). In the context of sustainable development, soil acidification is also associated with environmental degradation and disruption of soil ecosystem functions, including alterations in greenhouse gas emissions (C. Liu et al., 2023; Yin et al., 2023; Žurovec et al., 2021).

Soil acidification ultimately manifests as acidic soil conditions characterized by persistently low pH and gradual changes in the soil chemical environment over time (Chen et al., 2022; Shang et al., 2023). These conditions are widely distributed across tropical and subtropical regions and significantly constrain soil function and crop performance, making acidic soils a major concern for global food security (X. Zhu et al., 2024; Žurovec et al., 2021). Typically developing under high-rainfall environments with pH below 5.5, acidic soils promote increased

solubility of toxic ions such as aluminum (Al^{3+}) and iron (Fe^{3+}), which disrupt root systems, nutrient uptake, and plant physiological processes, ultimately reducing plant growth efficiency (Alemu et al., 2022; K. Li et al., 2025; Zhao et al., 2025b).

Beyond ion toxicity, acidic soils also reduce the availability of essential nutrients, particularly phosphorus (P), calcium (Ca), and magnesium (Mg), which are crucial for plant growth (Yigezu et al., 2023). Low-pH environments alter the soil–root interface, impair root functioning, and disrupt physiological regulation, thereby limiting nutrient acquisition, metabolic balance, and stress tolerance in plants (Lu et al., 2025; Yao et al., 2024). Prolonged exposure to these conditions weakens nutrient-use efficiency and diminishes soil function as a sustainable medium for crop production (W. Zhu et al., 2025). Consequently, nutrient imbalance disrupts vegetative and generative development, reduces agricultural productivity, and alters the structure and activity of microbes involved in key nutrient cycles, such as nitrogen and carbon (Enesi et al., 2024; Etana & Nebiyu, 2023; Sawargaonkar et al., 2025).

The multidimensional nature of the acidic soil problem, encompassing chemical, biological, and spatial interactions, highlights the need for soil-based interventions, as variability in soil pH and exchangeable cations can generate heterogeneous plant responses across agricultural landscapes (Chen et al., 2022; W. Zhu et al., 2025). Acidic soil amelioration, therefore, represents a crucial strategy aimed at restoring fundamental soil conditions, stabilizing the root environment, and supporting sustainable agricultural productivity. Although numerous studies have examined soil acidity dynamics, pH changes, and interactions among soil properties, existing findings remain fragmented across soil types, agroecological contexts, treatment materials, and research scales (Chen et al., 2022; W. Zhu et al., 2025). This fragmentation limits the development of an integrated understanding of acidic soil management and the comparative effectiveness of amelioration strategies.

Therefore, a systematic synthesis of recent scientific evidence is required to comprehensively evaluate the techniques, materials, and mechanisms involved in acidic soil

amelioration and their implications for soil fertility and crop productivity. The objective of this research was to systematically review and synthesize recent research on acidic soil amelioration strategies by classifying dominant techniques, identifying materials and application characteristics, and analyzing the mechanisms underlying improved soil fertility across diverse acidic soil conditions.

MATERIALS AND METHODS

Literature Search and Analysis

This study uses the SLR approach to systematically review various strategies for ameliorating acidic soils based on available scientific evidence. The SLR approach was chosen because it provides a comprehensive synthesis of various previous research results in a structured and transparent manner. The research procedure followed systematic stages, starting from data source identification, article selection based on inclusion criteria, to thematic synthesis relevant to the research focus.

The literature review process was conducted with reference to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) principles. Scientific articles were searched using the Scopus database, and the search strategy was designed to identify articles that explicitly discussed acid soil amelioration. The keywords used in the search process were a combination of the terms: “acid soil,” “soil fertility,” and “soil amelioration.” The search focused on research-based, open access articles.

Initial searches were conducted on the titles, abstracts, and keywords of articles to ensure high topic relevance. To maintain consistency and relevance of the studies analyzed, the following inclusion criteria were established: articles published between 2021 until 2025, full-text articles, experimental research results or research-based articles, and articles discussing techniques for dealing with acidic soil. The article selection process was carried out in several stages. In the initial stage, all articles found through the search were screened based on their titles and abstracts to eliminate duplicates and irrelevant studies. Next, articles that passed the initial screening stage were evaluated by

reading the full text to ensure they met the inclusion criteria. Based on this process, 38 articles were selected and used as data sources in this systematic review. tauu

Data from articles that met the inclusion criteria were analyzed, and data extraction was carried out systematically. The information extracted included bibliographic information (title, year of publication, and journal), research location and geographical conditions, initial soil conditions, amelioration techniques, materials and composition, scale and duration of treatment, final soil conditions, and changes in soil characteristics. All data were then synthesized,

which formed the basis for the thematic discussion in the results and discussion section.

Characteristics of Literature Review Studies

Table 1 showed the distribution of article sources based on publication journals, reflecting the diversity of disciplines and research approaches in the study of acid soil amelioration. All articles analyzed were from reputable international journals, most of which were in the Q1 quartile, indicating that the topic of acid soil amelioration has been widely studied in reputable scientific forums and was globally relevant.

Table 1. Sources and number of articles used

List of Journal	References (Ref.)	Information	Number of Articles
Science of the Total Environment	(Fernández-Caliani et al., 2024; X. Zhu et al., 2024)	Q1	2
Agriculture, Ecosystems and Environment	(Žurovec et al., 2021)	Q1	1
Applied Soil Ecology	(Kari et al., 2021; Zhou et al., 2024)	Q1	2
Heliyon	(Agegnehu et al., 2023; Alemu et al., 2022; Badiane et al., 2023; Becerra-Agudelo et al., 2022; Etana & Nebiyu, 2023; Kibet et al., 2023; Ndiaye et al., 2022; Yigezu et al., 2023)	Q1	8
Ecotoxicology and Environmental Safety	(Fan et al., 2023; Geng et al., 2022; He et al., 2025; B. Li et al., 2024; C. Liu et al., 2023; Shang et al., 2023; Yin et al., 2023)	Q1	7
Journal of Environmental Management	(K. Li et al., 2025; Lu et al., 2025; Peñalver-Alcalá et al., 2021; Zhao et al., 2025a)	Q1	4
Soil Biology and Biochemistry	(Bossolani et al., 2021; Chen et al., 2022)	Q1	2
Geoderma	(W. Zhu et al., 2025)	Q1	1
Environmental Chemistry and Ecotoxicology	(Zhao et al., 2025a)	Q1	1
Journal of Agriculture and Food Research	(Sawargaonkar et al., 2025)	Q1	1
Desalination and Water Treatment	(Słomkiewicz et al., 2025)	Q3	1
Environmental Technology & Innovation	(W. Liu et al., 2025; Yao et al., 2024; Zhang et al., 2024)	Q1	3
European Journal of Agronomy	(Bossolani et al., 2023)	Q1	1
Scientific Reports	(C. Li et al., 2023)	Q1	1
Soil & Tillage Research	(Jouichat et al., 2024)	Q1	1
Total Environment Microbiology	(Le et al., 2025)	ISSN: 3050-6417	1
Nutrient Cycling in Agroecosystems	(Ylivainio et al., 2024)	Q1	1
Total			38

RESULTS

The distribution of articles sourced from various reputable international journals shows the breadth of scientific attention to the issue of acidic soils. Based on this diversity of sources, further study focused on the geographical distribution and initial characteristics of acidic soils that were the subject of research in the 39 articles reviewed.

Geographical Distribution and Initial Conditions of Acidic Soil

This was the result of a synthesis of the geographical distribution and initial

characteristics of acidic soils studied in 38 articles, as shown in Table 2. This analysis provides an important context regarding the diversity of acidic soil environments studied in the literature and serves as a basis for understanding the variety of amelioration approaches and materials for acidic soil. The variations in initial soil acidity conditions identified in various agroecological regions form an important basis for determining the amelioration approaches applied by researchers. Research on acid soil amelioration was geographically widespread and covers various agroecological conditions (Table 2). Most studies were conducted in tropical and subtropical

regions, particularly in China, Ethiopia, Brazil, India, and other Asian countries. The most commonly reported soil types include Ultisols, Oxisols, Nitisols, red soils, and acidic agricultural soils contaminated with heavy metals

or originating from mining activities. The initial pH range of the soils in these studies was generally below 5.5, with some locations showing highly acidic conditions with pH <4.0.

Table 2. Geographic distribution and initial soil conditions

Country	Land Type/Use	Initial pH	Initial Conditions	Ref.
China (Subtropical)	Paddy & upland soils (calcareous & non-calcareous)	Calcareous soils: 6.9–8.6 non-calcareous soils: 5.0–6.9	Soil acidification due to natural and anthropogenic factors	(X. Zhu et al., 2024)
	Acidified brown soil	4.0	Acidification due to long-term N application	(Geng et al., 2022)
	Acidic mine tailings	~5.5	Fe ³⁺ & Al ³⁺ were very high	(Peñalver-Alcalá et al., 2021)
	Metal mining waste land	~5.5	Fe ³⁺ & Al ³⁺ were very high	(K. Li et al., 2025)
	Agricultural ultisol	<5.0	Highly mobilized Al	(Chen et al., 2022)
	Red soil region	~4.5	Agricultural intensification; low organic C	(W. Zhu et al., 2025)
	Tea garden soils	4.12–4.75	Stressed microbial communities	(Fan et al., 2023; B. Li et al., 2024; Zhao et al., 2025a)
	Acidic soil contaminated with Cd	<5.5	High available Cd at low pH	(C. Li et al., 2023; C. Liu et al., 2023; Shang et al., 2023)
	Acidic soil	<5.5	Acidic agricultural soil	(Yao et al., 2024)
	Acidic soil	-	Acidic dry soil	(He et al., 2025)
	Acidic soil	-	Purple acid soil (inceptisols or entisols), need to immobilize Al ³⁺	(He et al., 2025)
	Multi-type very acidic soil, ultisol & oxisol	<5.0	Highly soluble Al ³⁺	(Zhao et al., 2025b)
	Hydromorphic gley soil	5.5	Al toxicity limits growth	(Ndiaye et al., 2022)
	Sour tea plantation soil	<4.5	Magnesium deficiency	(W. Liu et al., 2025)
	Agricultural land	5.23	Degraded soil structure	(Lu et al., 2025)
Very acidic soil intensive	5.32	Low microbial activity	(Zhou et al., 2024)	
Acidic soil with industrial amendments	4.8	High N ₂ O emissions and organic content	(Yin et al., 2023)	
Nitisol (highlands)	-	Nitisol; high Exchangeable Acidity (EA) & Al ³⁺	(Alemu et al., 2022)	
Ethiopia (tropical)	Tropical agricultural land	<5.5	Low fertilizer response	(Agegnehu et al., 2023)
	Acid legume soil	<5.5	Low fertilizer response	(Etana & Nebiyu, 2023)
	Agricultural land with different land uses	<5.5	High P fixation	(Yigezu et al., 2023)
	Wheat acid soil	-	Low nutrient efficiency	(Ylivainio et al., 2024)
Ireland	Grassland soil	5.1	Brown soil with moderate drainage	(Žurovec et al., 2021)
Hungary	Sandy acidic soil	4.4	Poor in nutrients, low Cation Exchange Capacity (CEC)	(Kari et al., 2021)
Spanish	Iron-rich acidic mine soil (Technosol)	2.1–3.0	High phytotoxicity	(Fernández-Caliani et al., 2024)
India (tropical)	Acidic upland soil	<5.5	Finger millet productivity is low	(Sawargaonkar et al., 2025)
Poland (temperate climate)	Various acid soils	<5.5	Organo-mineral combination	(Słomkiewicz et al., 2025)
Senegal (tropical)	Acidic soil	<4.0	Acidic rice field soil	(Badiane et al., 2023)
Kenya (tropical)	Acidic soil	<5.5	Acidic and high Al Nitisols	(Kibet et al., 2023)
Colombia (humid tropical)	Acidic soil	4.8–5.2	Agricultural land contaminated with Ni	(Becerra-Agudelo et al., 2022)
Brazil (tropical)	Acidic soil	acid	Tropical acidic soil; low Soil Organic Matter (SOM)	(Bossolani et al., 2021)
	Long-term acidic soil	<5.5	Long-term lime treatment	(Bossolani et al., 2023)
Korea	Acidic agricultural land	acid	Acidic soil on agricultural land surface	(Zhang et al., 2024)
Multi-location (meta-data)	Dynamic acid soil (multi-location)	4.0–5.8	Temporal variation of pH	(Jouichat et al., 2024)
Vietnam	Acidic agricultural soil (tea plantation)	<5.5	Low crop productivity	(Le et al., 2025)

The dominant initial soil conditions include high exchangeable acidity, mobilization of aluminum and iron, low soil organic matter content, and pressure on the microbial soil community. These geographical variations and initial soil conditions indicate that acid soil problems occur across a wide and heterogeneous spectrum of environments.

Materials, Scale, and Duration of Acid Soil Amelioration Application

The diversity of amelioration techniques applied was further reflected in the variety of materials, research scale, and duration of application used. To provide a more detailed picture, the following results present a summary of amelioration approaches and their application characteristics.

Various approaches to acid soil amelioration have been applied with varying frequencies (Table 3). Liming was the most widely used approach, followed by biochar application, a

combination of biochar and organic matter, non-biochar organic matter, organomineral techniques, and industrial waste utilization. Each technique was applied under relatively similar initial pH conditions, generally below 5.5, but showed variations in the observed patterns of pH change and soil properties (Table 2).

Table 3 showed that there's a wide range of techniques or approaches for soil improvement. In liming, the most commonly used materials were calcium carbonate, calcium oxide, dolomite, and agricultural lime, with the scale of application dominated by field trials and durations ranging from one growing season to more than 15 years. Biochar and combinations of biochar with organic materials were generally applied on a pot, laboratory, and field scale, with durations ranging from several weeks to several years. Techniques based on non-biochar organic and organomineral materials were mostly carried out on an incubation and pot scale, with relatively shorter durations.

Table 3. Acidic soil amelioration approaches and their application characteristics

The approach used	Dominant Material Type	Research Scale	Application Duration	Ref.
Liming	CaCO ₃ , CaO, dolomite, agricultural lime, phosphogypsum	Dominant field	1 season – >15 years	(Agegnehu et al., 2023; Alemu et al., 2022; Bossolani et al., 2021, 2023; Etana & Nebiyu, 2023; Kibet et al., 2023; Le et al., 2025; K. Li et al., 2025; C. Liu et al., 2023; Sawargaonkar et al., 2025; Yigezu et al., 2023; Ylivainio et al., 2024; Žurovec et al., 2021)
Biochar	Plant residue biochar, sea shells, Urban Solid Refuse (USR) compost	Pot, lab, field	Week – 3 years	(Geng et al., 2022; He et al., 2025; Kari et al., 2021; Lu et al., 2025; Peñalver-Alcalá et al., 2021; Zhao et al., 2025b)
Biochar and Organic	Biochar and manure, compost, Seaweed Liquid Fertilizer (SLF)	Pots & fields	1 season – 5 seasons	(Badiane et al., 2023; Becerra-Agudelo et al., 2022; Chen et al., 2022; Ndiaye et al., 2022; Shang et al., 2023; Yao et al., 2024; Zhang et al., 2024)
Organic	Plant residue, organic compost	Incubation & field	65 days – 2 years	(Zhou et al., 2024; W. Zhu et al., 2025)
Organomineral	Sludge and slag, humic acid, C–mineral composite	Pot & lab	30 – 90 days	(Fan et al., 2023; Fernández-Caliani et al., 2024; W. Liu et al., 2025; Słomkiewicz et al., 2025; Zhao et al., 2025a)
Industrial waste	Phosphogypsum, alkaline waste	Lab	30 – 90 days	(C. Li et al., 2023; Yin et al., 2023)

The utilization of industrial waste was generally carried out on a laboratory scale with limited incubation time. These variations in scale and duration reflect the different research objectives and stages of development of the soil amelioration technologies being studied.

Soil Chemical Response to Various Approaches to Acid Soil Amelioration

Differences in materials, scale, and duration of application have implications for variations in soil response to amelioration treatments. Changes in soil chemical properties resulting from various soil amelioration techniques were closely related to In the use of non-biochar organic materials, changes in pH were followed by increases in soil organic carbon content and enzyme activity. Meanwhile, the organomineral category and industrial waste utilization showed responses in

the form of stabilization or increases in soil pH and decreases in heavy metal availability. Overall, these results indicate that soil acidification amelioration consistently modifies the soil chemical environment under various initial conditions and approaches used.

plant and environmental responses, as shown in Table 4. Analysis of soil chemical responses shows consistent patterns of change across all reviewed soil amendment approaches (Table 4). In liming, an increase in soil pH to above 5.5 was the most commonly reported response, accompanied by a decrease in aluminum mobilization and an increase in calcium and magnesium availability. The application of biochar and the combination of biochar with organic matter also showed an increase in soil pH as well as an increase in buffering capacity and cation exchange capacity.

Table 4. Approaches and impacts on acid soil amelioration

The Approach used	Initial pH Range	pH Change Trend	Changes in Soil Properties	Impact of Plants/Environment	Ref.
Liming	<4.0 – <5.5	– Increase to stable	Dissolved Al decreased, Ca & Mg increased, CEC & Soil Organic Carbon (SOC) increased	Increased yield, fertilizer efficiency, reduced N ₂ O emissions	(Agegnehu et al., 2023; Alemu et al., 2022; Bossolani et al., 2021, 2023; Etana & Nebiyu, 2023; Kibet et al., 2023; Le et al., 2025; K. Li et al., 2025; C. Liu et al., 2023; Sawargaonkar et al., 2025; Yigezu et al., 2023; Ylivainio et al., 2024; Žurovec et al., 2021)
Biochar	<5.5	Significant increase	Buffering pH, CEC & aggregation increased	Biomass increases, toxicity decreases	(Geng et al., 2022; He et al., 2025; Kari et al., 2021; Lu et al., 2025; Peñalver-Alcalá et al., 2021; Zhao et al., 2025b)
Biochar and Organic	<4.8 – 5.5	Increase	Available Al decreases, microbial activity increases	Biomass & crop yields increased	(Badiane et al., 2023; Becerra-Agudelo et al., 2022; Chen et al., 2022; Ndiaye et al., 2022; Shang et al., 2023; Yao et al., 2024; Zhang et al., 2024)
Organic (non-biochar)	4.1 – 5.3	Increase	SOC & enzyme activity increased	Soil acidification is reduced	(Zhou et al., 2024; W. Zhu et al., 2025)
Organomineral	2.1 – <5.5	Stable increasing	Heavy metals were immobilized, buffer capacity increases	Biomass increases, toxic risks decrease	(Fan et al., 2023; Fernández-Caliani et al., 2024; W. Liu et al., 2025; Słomkiewicz et al., 2025; Zhao et al., 2025a)
Industrial waste	~4.0	Increase	Enzyme activity & pH increase	Potential for improving soil function	(C. Li et al., 2023; Yin et al., 2023)

Conceptual Schematic of Acidic Soil Amelioration Mechanism

The positive effects on soil and plants observed in various studies highlight the importance of understanding the underlying processes. Therefore, Table 5 contains a synthesis of the mechanisms of acid soil amelioration. Table 5 shows the main mechanisms of acid soil amelioration identified from a systematic review of 38 scientific articles. These mechanisms include neutralization of soil acidity through acid-base reactions that reduce H^+ ion concentration, cation exchange between Ca^{2+}/Mg^{2+} and Al^{3+} and H^+ in soil adsorption complexes, and aluminum immobilization through the formation of less soluble or

chemically bound forms of Al. In addition, an increase in pH buffering capacity and cation exchange capacity due to the contribution of surface charges and functional groups of ameliorants was also demonstrated. The mechanisms of adsorption and complexation of heavy metals were described as processes that reduce the bioavailability of Cd, Zn, and Ni through interactions with organic and mineral surfaces. On a soil biology scale, soil acidification amelioration has been shown to increase soil organic carbon content, microorganism activity, and soil enzyme function, which collectively contribute to improving the root environment and reducing greenhouse gas emissions such as N_2O .

Table 5. Mechanisms of acidic soil amelioration

Mechanism Category	Main Mechanism	Amelioration Approaches	Mechanism Process	Ref.
Neutralization of soil acidity	Neutralization of H^+ ions and increase in soil pH	Liming	Chemistry	(Agegnehu et al., 2023; Alemu et al., 2022; Kibet et al., 2023; K. Li et al., 2025; C. Liu et al., 2023; Yigezu et al., 2023; Ylivainio et al., 2024; Žurovec et al., 2021)
Cation exchange in adsorption complexes	Exchange of Ca^{2+}/Mg^{2+} with Al^{3+} and H^+	Liming, Organomineral	Chemistry	(Alemu et al., 2022; Bossolani et al., 2021, 2023; Etana & Nebiyu, 2023; K. Li et al., 2025; Sawargaonkar et al., 2025)
Immobilization of aluminum (Al^{3+})	The decrease in Al could be exchanged and the Al dissolved	Biochar, Biochar and Organic, Organomineral	Chemistry	(He et al., 2025; W. Liu et al., 2025; Ndiaye et al., 2022; Zhao et al., 2025b)
Increased pH buffering capacity	Soil pH stability through increased buffer capacity	Biochar, Organomineral	Physics–chemistry	(Geng et al., 2022; Kari et al., 2021; Lu et al., 2025; Słomkiewicz et al., 2025)
Adsorption and complexation of heavy metals	Reduction of bioavailable Cd, Zn, Ni through adsorption/complexation	Biochar, Organomineral, Industrial waste	Chemistry	(Becerra-Agudelo et al., 2022; Fan et al., 2023; Fernández-Caliani et al., 2024; B. Li et al., 2024; C. Li et al., 2023; Zhao et al., 2025a)
Increased CEC	Increased CEC and ground surface load	Biochar, Biochar and Organic	Physics–chemistry	(Geng et al., 2022; Lu et al., 2025; Peñalver-Alcalá et al., 2021)
Increase in SOC	Increased C-organic content and aggregate stability	Organic, Biochar, Biochar and Organic	Biochemistry	(Badiane et al., 2023; Bossolani et al., 2021; Chen et al., 2022; Zhou et al., 2024; W. Zhu et al., 2025)
Stimulation of soil microbial and enzyme activity	Increased microbial biomass and soil enzyme activity	Biochar, Organic, Industrial waste	Biology	(Kari et al., 2021; Le et al., 2025; C. Li et al., 2023)
Reducing greenhouse gas emissions (N_2O)	Reduction of N_2O emissions and changes in the nitrification–denitrification process	Liming, Industrial waste	Biochemistry	(C. Liu et al., 2023; Yin et al., 2023; Žurovec et al., 2021)

DISCUSSION

Liming as the Primary Strategy for Acidic Soil Amelioration

The dominance of liming identified in the Results reflects its nature as the most direct and predictable amelioration approach in addressing soil acidity. Lime works through the mechanism of H⁺ ion neutralization and exchangeable Al³⁺ precipitation, thereby providing a rapid response to increased soil pH and restoration of base cation balance (Alemu et al., 2022; Kibet et al., 2023; K. Li et al., 2025; C. Liu et al., 2023). This advantage explains why liming is widely applied on a field scale and used as the primary approach in intensive agricultural systems. Furthermore, it also explains why the effectiveness of liming is not uniform in all soil conditions. Variations in the type of lime material, dosage, and duration of application result in different soil responses, especially in soils with low buffering capacity or significant biological degradation (Bossolani et al., 2023; B. Li et al., 2024; K. Li et al., 2025). This indicates that although liming is effective in improving soil chemistry, comprehensive soil function recovery often requires additional approaches, especially in acidic soils that have undergone long-term degradation.

Functional Role of Biochar in Addressing Chemical and Physical Constraints of Acidic Soils

The prominent role of biochar reflects its ability to simultaneously address the chemical and physical limitations of acidic soils. Unlike liming, which works primarily through rapid chemical reactions, biochar provides a more gradual effect by increasing Al³⁺ adsorption and soil buffering capacity (Geng et al., 2022; He et al., 2025; Słomkiewicz et al., 2025). This mechanism allows biochar to function as a medium to long-term buffer against soil acidity fluctuations.

Biochar is often applied on a pot and laboratory scale, reflecting the complexity of variables that influence its effectiveness, such as raw materials, pyrolysis temperature, and chemical modification (W. Liu et al., 2025; Lu et al., 2025; Zhao et al., 2025b). This explains why biochar's response to acidic soils is more variable

than liming, but under certain conditions it provides more sustainable soil improvement.

Synergistic Effects of Biochar–Organic Combinations on Soil Biological Recovery

The combination approach of biochar and organic matter identified in the Results shows synergy between chemical improvement and biological restoration of the soil. Biochar provides a stable physical and chemical matrix, while organic matter serves as a source of carbon and energy for soil microorganisms (Ndiaye et al., 2022; Shang et al., 2023). This combination creates a microenvironment that is more conducive to soil biological activity than either application alone. This indicates that this combinatorial approach is particularly relevant for acidic soils with strong biological degradation, where increasing pH alone is not sufficient to restore soil function. Thus, the biochar–organic combination can be understood as a transitional strategy towards a more complex and resilient soil ecosystem restoration.

Limitations of Organic Amendments without Alkaline Components

The synthesis of 38 articles shows that organic materials lacking alkaline components play a more limited role in ameliorating soil acidification. The reported increases in organic carbon and microbial activity Yao et al. (2024); Zhou et al. (2024); W. Zhu et al. (2025) were not always accompanied by significant improvements in soil pH or reductions in Al³⁺ toxicity. This suggests that the main mechanism of organic materials is biological rather than chemical. These findings confirm that the use of organic matter alone is less effective in soils with high acidity and heavy metal loads. However, organic matter still has a strategic role as a supporting component in integrated amelioration systems, especially for maintaining the sustainability of soil biological functions.

Organomineral and Industrial Waste Approaches for Severely Degraded Acidic Soils

The organomineral approach and utilization of industrial waste have emerged as specific strategies for acidic soils with extreme levels of

degradation. The dominant mechanisms include increasing soil buffering capacity and immobilizing heavy metals through more complex chemical reactions (C. Li et al., 2023; Peñalver-Alcalá et al., 2021; Yin et al., 2023; Zhao et al., 2025a). This explains why this approach is widely applied to contaminated or post-mining soil conditions. However, the application of this approach is still limited and contextual, with most studies conducted on a laboratory scale. This reflects the need for long-term evaluation of chemical stability and potential environmental impacts before this approach can be widely adopted.

Implications of Mechanistic Diversity for Adaptive Soil Amelioration Strategies

The diversity of identified amelioration mechanisms confirms that acidic soils are complex systems that require adaptive approaches. Chemical neutralization, Al^{3+} immobilization, organic carbon accumulation, and microbial community restoration work through complementary rather than mutually exclusive pathways. These findings imply that effective soil acidification amelioration strategies cannot be standardized, but must be tailored to the initial soil conditions, degradation level, and land management objectives. Thus, these SLR results provide a scientific basis for the development of more flexible and sustainable amelioration strategies.

CONCLUSION

Acidic soils constitute a complex constraint to soil fertility due to low pH, Al^{3+} toxicity, nutrient imbalance, and degradation of soil biological functions, particularly in tropical and subtropical regions dominated by Ultisols, Oxisols, and Nitisols. This systematic literature review shows that liming remains the most widely applied amelioration strategy because of its effectiveness in increasing soil pH and reducing exchangeable Al; however, its performance is highly dependent on material type, dosage, and application duration, and may be insufficient under severe soil degradation. Biochar, especially when combined with organic amendments, offers a multifunctional alternative by improving

chemical, physical, and biological soil properties. In contrast, amendments alone mainly support biological recovery with limited effects on soil acidity. Organomineral amendments and industrial by-products demonstrate potential for rehabilitating severely degraded acidic soils, although their application remains context-specific. This review highlights that no single amelioration strategy is universally applicable, and effective management of acidic soils requires adaptive, site-specific approaches that integrate appropriate techniques, materials, and initial soil conditions, rather than relying on simple pH adjustment.

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