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Sustainable Management and Productive Utilisation of Acid Soils: A Critical Synthesis of Amendments, Biological Adaptation and Systems-Level Trade-offs

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Authors' contributions

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

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Review Article

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Abstract

Acid soils constrain crop production through interacting chemical, biological and physical processes rather than low pH alone. Aluminium and manganese toxicity, depletion of base cations, restricted phosphorus availability, impaired root exploration and shifts in soil biota can occur at different depths and with markedly

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different severity among soils. This critical narrative review evaluates strategies for the sustainable management and productive utilisation of acid soils, with emphasis on agricultural topsoils and subsoils, amendment choice, biological adaptation, integrated nutrient management, implementation constraints and environmental safeguards. Peer-reviewed literature published from January 1990 to 30 May 2026 was selected through transparent searches of accessible scholarly indexes, supplemented by citation chasing and verification of bibliographic records and digital object identifiers. The evidence is strongest for correctly diagnosed, crop-specific liming of the cultivated layer. Nevertheless, average responses conceal substantial heterogeneity associated with initial acidity, buffering capacity, amendment quality, placement, soil depth, water regime, crop sensitivity and co-limiting nutrients. Gypsum can improve calcium supply and alleviate aluminium constraints below the limed layer, but it is not a substitute for acid neutralisation and can redistribute magnesium or potassium. Organic amendments and biochar may complex aluminium, supply nutrients and improve buffering, yet their effects depend on composition, dose, decomposition and contaminant control. Acid-tolerant crops, root traits and rhizosphere processes extend productive options but rarely remove the need to correct severe chemical constraints. The most defensible strategy is therefore a profile-based sequence: diagnose active and reserve acidity by depth, set a crop- and soil-specific target, apply quality-assured amendments at an effective placement and rate, correct nutrient imbalances, use adapted germplasm, retain organic resources and monitor re-acidification. Sustainability appraisal must include quarrying and transport, greenhouse-gas accounting, nutrient leaching, biodiversity, land-use change, affordability and amendment quality. Productive utilisation should prioritise already-cleared or degraded acid land and should not be used to justify conversion of intact acid-soil ecosystems. Long-term, depth-resolved and economically explicit field experiments remain the principal evidence need.

Keywords: Aluminium toxicity; biochar; gypsum; integrated soil fertility management; liming; phosphorus-use efficiency; subsoil acidity.

1. Introduction

Acid soils occupy a major share of the terrestrial surface and include highly weathered tropical soils, leached temperate soils and agricultural soils that have acidified under management. A frequently cited global synthesis estimated that acid soils cover approximately 30% of the ice-free land surface, although the agriculturally relevant extent depends on the pH threshold, soil depth and crop sensitivity used in classification (von Uexküll & Mutert, 1995). Soil acidity is therefore not a single soil class or a uniform production problem. It is a condition in which proton activity, exchangeable acidity, aluminium and manganese chemistry, nutrient availability and biological functioning interact. A soil with a pH of 5.2 may be manageable for one crop but severely restrictive for another, while two soils at the same measured pH may differ greatly in reserve acidity and lime requirement because of contrasting clay mineralogy, organic matter and buffering capacity (Fageria & Baligar, 2008; Goulding, 2016; Nguyen, 2023).

Natural acidification results from weathering, leaching of basic cations, organic-acid production and long-term pedogenesis. Agricultural production can accelerate the process through nitrification of ammonium-based fertilisers, nitrate leaching accompanied by calcium, magnesium or potassium, biological nitrogen fixation when nitrate is not fully retained, export of alkalinity in harvested products and limited return of residues (Bolan et al., 1991; Goulding, 2016; Hinsinger et al., 2003). The scale of management-induced change can be large. Long-term observations in major Chinese croplands documented substantial pH decline under intensified fertilisation, while global experimental synthesis indicates that nitrogen addition commonly acidifies soils, with the magnitude conditioned by climate, initial pH and ecosystem properties (Guo et al., 2010; Tian & Niu, 2015). Crop-residue retention and reduced nitrogen inputs can slow this trajectory in some systems, but prevention is not equivalent to correction where exchangeable aluminium is already high or base cations have been depleted (Zuo et al., 2023).

The agronomic expression of acidity is dominated by constraints to roots. As pH declines, aluminium-bearing minerals and exchange sites can release phytotoxic Al^{3+}, while manganese may also reach toxic activity. Sensitive roots show rapid inhibition of elongation, reduced branching and impaired water and nutrient capture. At the same time, calcium and magnesium may be deficient, phosphorus can be sorbed by aluminium and iron oxides, molybdenum availability may decline, and biological nitrogen fixation can be suppressed. A global meta-analysis assembled 1,760 observations from 101 studies and estimated an average crop-yield reduction of

13.7% under soil acidification, alongside a 25.4% reduction in root length; the spread of responses was nevertheless wide and varied among crop groups and soil conditions (Du et al., 2024). These averages demonstrate material risk but do not provide a universal treatment threshold.

Recent synthesis further indicates that plant responses to aluminium stress involve coordinated exclusion and internal detoxification mechanisms, and that their effectiveness varies with genotype, developmental stage and the surrounding chemical environment (Kocjan et al., 2025).

Management has traditionally centred on carbonate liming. This emphasis is justified because lime neutralises acidity, increases calcium or magnesium supply and reduces aluminium activity when the material is reactive and placed within the affected layer. Global and regional syntheses consistently show positive average effects on pH, yield and, in many settings, profitability (Enesi et al., 2023; Fageria & Baligar, 2008; Zhang et al., 2023). Yet the apparent simplicity of "raise pH with lime" has obscured several recurrent failures. Soil pH alone is often used to prescribe rates without measuring buffer acidity or aluminium saturation; product fineness and neutralising value may be unknown; surface applications may correct only the upper centimetres; nutrient deficiencies may remain after aluminium stress is relieved; and the economically optimum pH can differ from the biological maximum for a particular crop (Holland & Behrendt, 2021; Holland et al., 2019; Nguyen, 2023).

Recent evidence also broadens the management question. Meta-analysis of 832 observations from 142 papers found that lime, biochar, organic materials, industrial by-products and their combinations generally increased pH and yield, but response magnitude depended on initial pH, soil texture, organic matter, duration and cost (Zhang et al., 2023). A separate field-based meta-analysis concluded that liming was more effective when incorporated than when left on the surface and that profitability varied by crop and application rate (Enesi et al., 2023). Research on subsoil acidity has meanwhile shown that surface pH correction may leave an acid, aluminium-rich zone below the cultivated layer, restricting rooting and drought resilience (Hettithanthri et al., 2026). These findings shift the problem from choosing a single amendment to matching mechanisms, depth, timing, crop traits and resources.

Recent global evidence on biochar similarly shows that its capacity to ameliorate soil acidity is contingent on biochar properties, initial soil pH, cation-exchange capacity, climate and management, thereby reinforcing the need for site- and product-specific evaluation (Zhang et al., 2025).

Experimental evidence further suggests that combining lime with a characterised organic amendment can improve soil acidity indicators and phosphorus availability, although accompanying changes in micronutrient availability require balanced monitoring (Regasa et al., 2025).

Biological adaptation is an equally important part of productive utilisation. Aluminium-resistant crops may exclude Al^{3+} through organic-anion exudation, sequester absorbed aluminium, modify rhizosphere pH or maintain growth through tolerant root architecture. Molecular studies have identified aluminium-activated malate transporters in wheat and citrate-transporting MATE proteins in sorghum, while rice phosphorus-efficiency research illustrates how root traits can improve nutrient capture in low-phosphorus soils (Gamuyao et al., 2012; Magalhaes et al., 2007; Sasaki et al., 2004). These advances support breeding and crop choice, but many mechanistic results derive from solution culture or controlled environments. Field performance remains contingent on drought, nutrient supply, pathogen pressure, soil profile and the intensity of acidity, so genetic tolerance should be treated as a complement to, not a replacement for, soil correction (Kochian et al., 2015; Zhu & Shen, 2024).

Emerging field evidence also indicates that selected root-associated microbial communities may enhance crop tolerance to aluminium toxicity and improve phosphorus acquisition in acidic soils, although their wider applicability remains to be established across crops and environments (Liu et al., 2023).

The term "sustainable utilisation" also requires a land-use boundary. Acid-soil management can increase production on existing cropland, restore degraded fields and support acid-adapted pasture, tree and mixed systems. It should not imply that intact tropical forests, peatlands or other naturally acidic ecosystems are underused and available for conversion. The sustainability test is whether intervention improves long-term productivity and soil function on land already committed to production while limiting off-site pollution, greenhouse-gas burdens, biodiversity loss and dependence on unaffordable inputs. This distinction is essential because the technical capacity to raise pH does not establish an ecological or social case for agricultural expansion.

Several reviews have addressed tropical acid-soil chemistry, liming, crop responses, soil biota, biochar or subsoil acidity (Agegnehu et al., 2021; Fageria & Baligar, 2008; Hettithanthri et al., 2026; Holland et al., 2018; Wenyika et al., 2025a). Their conclusions are valuable but remain partitioned by amendment, region or disciplinary perspective. A management decision, by contrast, must connect diagnosis, profile depth, amendment quality, crop adaptation, nutrient balance, economics and environmental trade-offs. The present synthesis addresses that integration and gives particular attention to why apparently effective interventions fail when transferred across soils or scales.

1.1 Scope, Research Gap and Objectives

This review evaluates the sustainable management and productive agricultural utilisation of mineral acid soils in annual cropping, perennial cropping, pasture and agroforestry contexts. It focuses on topsoil and subsoil acidity, aluminium and manganese constraints, nutrient interactions, carbonate liming, gypsum, organic amendments, biochar, adapted germplasm, rhizosphere processes, integrated nutrient management, implementation economics and environmental safeguards. Acid sulphate soils, mine wastes, contaminated industrial sites and forest liming are excluded except where evidence clarifies a transferable mechanism or risk. The principal gap is the absence of a profile-based, systems-level synthesis that distinguishes acid neutralisation from complementary calcium, nutrient and biological functions while incorporating affordability and environmental consequences. The objectives are to evaluate the strength and limits of the principal interventions, explain response heterogeneity, integrate chemical correction with biological adaptation, define a defensible decision sequence for different production contexts and identify research priorities that would improve long-term and field-scale management.

2. Methods for Literature Selection

This section describes a transparent literature-selection process appropriate to a critical narrative review. It was designed to identify influential mechanisms, field evidence, quantitative syntheses, conflicting findings and implementation studies rather than to produce an exhaustive census of every experiment. No screening counts are reported because a prospectively logged systematic-review workflow was not undertaken.

2.1 Review Design and Rationale

A critical narrative design was selected because the review question spans soil chemistry, plant physiology, microbiology, agronomy, economics and environmental assessment, and because the available evidence includes mechanistic experiments, long-term field trials, regional case studies, reviews and meta-analyses with non-equivalent outcomes. A single quantitative effect estimate would not adequately represent differences in soil depth, amendment composition, crop target, time horizon or implementation setting. The review nevertheless followed the transparency and quality principles embodied in the Scale for the Assessment of Narrative Review Articles, including explicit justification, stated objectives, a reproducible search description, evidence-based reasoning and appropriate presentation of data (Baethge et al., 2019). Narrative design was not treated as permission for unsystematic source selection; instead, evidence was appraised for design quality, relevance and claim support.

2.2 Information Sources

Searches were conducted in FAO AGRIS, the Directory of Open Access Journals, PubMed and Semantic Scholar. These sources were selected to cover agronomy, soil science, environmental science, plant biology and accessible interdisciplinary literature. Supplementary discovery used backward citation searching from recent high-quality reviews and meta-analyses, forward citation searching, related-article searching, institutional scholarly repositories and DOI landing pages. Publisher or journal websites were used only to verify bibliographic metadata, article status and the relationship between a claim and its source; they were not described as literature databases. Searches for corrections, retractions and bibliographic inconsistencies were undertaken during final reference verification.

2.3 Search Strategy and Search Period

The main search period was January 1990 to 30 May 2026. Earlier publications were retained when they established a mechanism, global distribution estimate or long-term conceptual basis that remained necessary for interpretation. Search concepts combined the condition, intervention, mechanism, outcome and implementation dimensions. Representative strings included: (“acid soil*” OR “soil acidification” OR “subsoil acidity”) AND (lime OR liming OR gypsum OR “organic amendment*” OR biochar OR “crop residue*”) AND (yield OR root* OR “aluminium toxicity” OR “aluminum toxicity” OR phosphorus); (“acid-tolerant” OR “aluminium resistance” OR “aluminum resistance” OR ALMT OR MATE OR “phosphorus-use efficiency”) AND (crop* OR pasture OR agroforestry); and (“soil acidity” AND (econom* OR adoption OR “value chain” OR “greenhouse gas*” OR leaching OR biodiversity)). Searches were iteratively refined with crop names, soil-profile terms and regional terms when broad results were dominated by unrelated ecological or contaminated-site literature.

2.4 Eligibility Criteria

Eligible sources were peer-reviewed original studies, meta-analyses and scholarly reviews that directly addressed the formation, diagnosis, consequences or management of agricultural soil acidity. Field evidence was prioritised for effectiveness and implementation claims, while pot, column, incubation, molecular and hydroponic studies were included when they clarified mechanisms that could not be isolated readily in the field. Studies of annual crops, pastures, perennial crops and agroforestry were eligible across climatic regions. English-language publications were used because dependable full-text appraisal and bibliographic verification were required. Foundational pre-1990 evidence was considered only when later literature continued to rely on the mechanism or estimate.

Sources were excluded when bibliographic identity or DOI could not be verified; when they were retracted or superseded without analytical reason to discuss them; when they concerned acid mine drainage, engineering stabilisation, aquatic acidification or acid sulphate soils without transferable agricultural relevance; when they were promotional, anonymous or non-scholarly; or when only an abstract was available and the claim required methods or results not reported there. Preprints were not used as evidence of effectiveness. Studies that reported pH change without sufficient amendment characterisation, baseline soil information or crop context were used cautiously and not as the sole support for recommendations.

2.5 Screening, Duplicate Handling and Study Selection

Titles and abstracts were assessed for direct relevance to agricultural acid-soil processes or management. Full texts were then examined for the soil condition, depth sampled, crop or land use, amendment source and rate, comparator, duration, measured outcomes and interpretation. Duplicate records were identified manually using title, first author, publication year and DOI; the version of record with the most complete metadata was retained. Selection gave priority to recent quantitative syntheses, long-term and multi-location field studies, studies testing response moderators, and seminal mechanism papers needed to interpret field outcomes. Regional evidence was retained when it illuminated access, value chains or production contexts not represented in global syntheses. Inaccessible or bibliographically unresolved records were excluded rather than inferred from secondary citations.

2.6 Critical Appraisal and Evidence Synthesis

Evidence was appraised according to study design, replication, duration, baseline acidity, soil texture and mineralogy, depth resolution, amendment characterisation, placement, control treatments, crop sensitivity, nutrient co-treatments, statistical adequacy, external validity and consistency with independent evidence. Meta-analyses were assessed for the comparability of included studies, field versus controlled-environment balance, moderator analysis and whether average effect sizes concealed strong residual heterogeneity. Mechanistic studies were judged by the extent to which the experimental medium and exposure represented field soil. Economic evidence was assessed for time horizon, residual amendment value, transport and application costs, output prices and whether benefits were attributed solely to acidity when other constraints were present.

Themes were developed around causal processes and management decisions: diagnosis, surface and subsoil correction, organic and pyrogenic amendments, nutrient interactions, biological adaptation, systems integration, implementation and environmental safeguards. Convergent evidence was distinguished from context-dependent or preliminary evidence. Apparent conflicts were interpreted in relation to initial pH, reserve acidity, aluminium saturation, amendment reactivity, soil depth, moisture, crop species, trial duration and co-limiting nutrients. Recommendations were retained only where the underlying mechanism and field evidence were mutually consistent or where uncertainty was stated explicitly.

3. Acid-Soil Processes and the Logic of Intervention

Effective management begins by identifying which expression of acidity limits the intended land use. Soil pH is indispensable, but it measures active acidity in a defined extract and does not directly quantify the pool of exchangeable or reserve acidity that will consume amendment. The same laboratory pH can therefore correspond to different lime requirements. Water pH, salt pH, buffer pH, exchangeable acidity and aluminium saturation answer related but non-interchangeable questions. Texture, clay mineralogy and organic matter determine buffering, while the crop determines the biological consequence. A coarse soil with weak buffering may change pH rapidly but re-acidify quickly; a highly weathered clay may require more neutralising material and may retain substantial phosphorus even after pH increases (Fageria & Baligar, 2008; Nguyen, 2023; Wenyika et al., 2025b).

3.1 Formation, Buffering and Anthropogenic Intensification

In humid environments, prolonged weathering and leaching remove calcium, magnesium, potassium and sodium and leave exchange complexes increasingly occupied by hydrogen and aluminium. The hydrolysis of soluble aluminium then generates additional protons, creating a coupled acidity system rather than a simple excess of hydrogen ions. Variable-charge minerals add another layer: as pH declines, negative charge and cation-exchange capacity may fall, reducing retention of nutrient cations. Raising pH can restore charge, but the response depends on mineralogy and organic matter. This is why a target based only on a fixed pH value can over-treat one soil and under-treat another (Fageria & Baligar, 2008; Goulding, 2016; Wenyika et al., 2025b).

Agriculture changes both proton production and alkalinity removal. Nitrification generates acidity, but the net soil effect depends on whether nitrate is taken up or leached and whether associated base cations are retained. Legume-based systems can acidify when fixed nitrogen is converted and nitrate escapes the rooting zone, even though biological fixation itself is not invariably acidifying. Harvest removes cations accumulated by plants, particularly when whole biomass or forage is exported. Repeated fertiliser use without residue return or replacement of exported bases can therefore create an acidity debt that becomes visible only after several seasons (Bolan et al., 1991; Goulding, 2016; Hinsinger et al., 2003). Evidence from Chinese croplands illustrates how high nitrogen inputs and product removal can overwhelm buffering, whereas combined residue return and nitrogen reduction can moderate further decline (Guo et al., 2010; Zuo et al., 2023).

Prevention deserves greater emphasis because correction becomes more expensive as acidity penetrates the profile. Balanced nitrogen management, synchronising fertiliser supply with crop demand, retaining non-diseased residues, avoiding unnecessary ammonium inputs, recycling organic resources and periodically replacing exported calcium and magnesium all reduce the rate of re-acidification. These practices cannot neutralise severe existing acidity rapidly, but they extend the residual life of corrective amendments. Their effectiveness is also conditional: residue decomposition can transiently increase pH through decarboxylation and organic anions, yet later nitrification can reverse part of the effect. Claims that residue return “solves” acidity should therefore be restricted to systems where acid production and alkalinity export are also reduced (Haynes & Mokolobate, 2001; Zuo et al., 2023).

3.2 Aluminium, Manganese and Nutrient Constraints

Aluminium toxicity is the most widely generalisable root constraint in strongly acid mineral soils, but neither total aluminium nor pH alone predicts injury reliably. Toxicity depends on the activity and speciation of Al in soil solution, exchangeable Al, ionic strength, dissolved organic ligands and crop sensitivity. The root apex is a principal target: aluminium can alter cell-wall properties, membrane function, signalling and cytoskeletal processes, rapidly slowing elongation. Reduced exploration then produces secondary water and nutrient stress, particularly during dry periods (Bojórquez-Quintal et al., 2017; Kochian et al., 2015; Zhu & Shen, 2024). The field symptom may resemble drought or phosphorus deficiency, so diagnosis should connect soil tests with root distribution and crop history.

Manganese toxicity is less consistently measured but can be decisive in waterlogged or strongly acid soils. Excess Mn^{2+} interferes with photosynthesis and enzyme systems and can produce foliar symptoms even when aluminium is the dominant root-zone concern. Liming generally reduces soluble aluminium and manganese, but the crop-specific threshold and soil redox regime matter. A rate sufficient to suppress aluminium may not address manganese under fluctuating saturation, and overliming can reduce availability of iron, zinc, copper, boron or manganese below crop requirements. The objective is not maximal pH but a range in which toxic activities are controlled while nutrient supply remains balanced (Fageria & Baligar, 2008; Holland et al., 2018; Wenyika et al., 2025b).

Phosphorus illustrates the non-linearity of pH management. At low pH, phosphate is strongly sorbed by aluminium and iron oxides and may precipitate with aluminium or iron; root inhibition further reduces acquisition. Moderate liming can increase effective rooting volume and reduce some aluminium-associated fixation, but high pH or excessive calcium can favour sparingly soluble calcium phosphates. The familiar claim that phosphorus availability peaks near neutrality is an oversimplification because texture, oxide content, organic matter, fertiliser placement and extractant alter the response (Penn & Camberato, 2019). Root traits, carboxylate exudation and microbial activity also influence access to sorbed pools (Lambers et al., 2006; Richardson et al., 2009). Consequently, phosphorus fertiliser should be calibrated after acidity diagnosis and often applied with, rather than long before, corrective treatment.

Deficiencies of calcium and magnesium can be direct constraints rather than mere correlates of acidity. Potassium may also be vulnerable to leaching when exchange capacity is low, while molybdenum limitation can restrict legume nodulation. Liming material selection can partly address this: calcitic lime supplies calcium, whereas dolomitic material supplies calcium and magnesium. Yet using dolomite solely because soil is acid can create an unnecessary magnesium load, and using calcite where magnesium is deficient can leave a residual limitation. Tissue testing and exchangeable-cation analysis are therefore more defensible than treating all acid soils as chemically equivalent.

3.3 Rhizosphere, Microbiome and Subsoil Dimensions

Roots modify the pH of their immediate environment through unequal cation and anion uptake, proton or hydroxyl release, organic-anion exudation and respiration. These rhizosphere effects can locally reduce aluminium activity or mobilise phosphorus, but they occur over millimetres and do not neutralise the bulk reserve acidity of a severely constrained profile (Hinsinger et al., 2003). The practical implication is that crop traits can improve access within an acid soil but cannot be assumed to replace amendment where the soil solution remains toxic. Conversely, a crop may tolerate bulk soil pH that would be unsuitable for a sensitive legume, so crop sequence and pH target should be planned together.

Soil pH is also a powerful ecological filter. Continental and field-gradient studies show pronounced shifts in bacterial community composition across pH, while fungal communities often display a different or broader response range (Lauber et al., 2009; Rousk et al., 2010). Liming may increase bacterial activity, nitrification, residue decomposition and some components of soil fauna, but change is not uniformly beneficial. Faster mineralisation can increase short-term nutrient supply while exposing nitrate to leaching; pathogen and disease-suppressive relationships can also shift. Reviews of agroecosystem biota indicate that outcomes depend on original pH, land use, rate and time since application, with much less evidence for function than for community composition (Wenyika et al., 2025a).

Subsoil acidity is the major diagnostic blind spot. Surface samples can indicate an acceptable pH while roots encounter high aluminium saturation at 15-40 cm. The problem is especially important in no-till systems, perennial systems and regions where surface-applied carbonate moves slowly. Restriction at depth reduces access to stored water and makes yield response to topsoil correction unstable across seasons. Recent synthesis emphasises that most experiments and routine sampling remain topsoil-centred and that field-tested options for rapid subsoil correction are limited (Hettithanthri et al., 2026). Depth-resolved sampling should therefore precede claims that a field is “corrected”. The relevant increments depend on tillage and rooting pattern, but separate topsoil and upper-subsoil samples are a minimum where stratification is plausible.

Table 1 translates these processes into diagnostic distinctions. Its central implication is that a management prescription should be triggered by a constraint profile, not by a single pH reading. Combining pH with buffer or exchange acidity, aluminium saturation, exchangeable bases, phosphorus status, texture, organic matter, depth and crop sensitivity reduces both under-treatment and overliming.

Table 1. Diagnostic distinctions that determine acid-soil management

Diagnostic dimension	Evidence and interpretation	Management implication	Supporting references
Active versus reserve acidity	Measured pH indicates proton activity in the test suspension; buffer or exchange acidity indicates the larger pool that resists change. Soils at the same pH can therefore have different lime requirements.	Specify the pH method and use a calibrated lime-requirement test where buffering is substantial.	(Goulding, 2016; Nguyen, 2023)
Aluminium toxicity	Al^{3+} activity and aluminium saturation can restrict root elongation before visible shoot symptoms. Organic ligands, pH, clay and depth alter toxicity.	Measure exchangeable aluminium or aluminium saturation by depth and use crop-specific sensitivity rather than pH alone.	(Bojórquez-Quintal et al., 2017; Kochian et al., 2015)
Manganese toxicity and redox	Manganese availability depends on pH, oxidation-reduction conditions and crop sensitivity; waterlogging can intensify toxicity independently of aluminium.	Combine acidity correction with drainage and avoid attributing all root injury to aluminium.	(Fageria & Baligar, 2008; Lauricella et al., 2020)
Phosphorus and base-cation constraints	Phosphorus sorption by aluminium and iron phases can coincide with low calcium and magnesium. Liming may improve root access but does not guarantee adequate phosphorus.	Diagnose and correct acidity and nutrient limitation jointly; avoid phosphorus over-application or indiscriminate dolomitic lime.	(Penn & Camberato, 2019; Zhang et al., 2023)
Subsoil acidity	A favourable surface layer can overlie acidic, calcium-poor subsoil that limits rooting and drought resilience. Surface amendment moves downward slowly in many systems.	Sample by depth; distinguish the need for neutralisation, soluble calcium or deep placement.	(Fontoura et al., 2019; Hettithanthri et al., 2026)
Re-acidification pressure	Ammonium fertilisation, nitrate leaching, product removal and residue export consume alkalinity after correction.	Link maintenance liming to nitrogen balance, harvest export, residue return and repeated profile monitoring.	(Bolan et al., 1991; Guo et al., 2010; Zuo et al., 2023)

Note. Al^{3+} = trivalent aluminium ion. The distinctions are diagnostic rather than exhaustive and should be interpreted with locally calibrated soil-test methods

4. Amendment Strategies: Efficacy, Limits and Context

Amendments differ in the processes they control. Carbonates neutralise protons and precipitate or hydrolyse aluminium; gypsum supplies mobile calcium and sulphate but has little direct acid-neutralising capacity; organic materials provide alkalinity, ligands, nutrients and carbon in proportions that vary by source; and biochar combines ash alkalinity, surface charge and persistent carbon to a degree governed by feedstock and pyrolysis. Comparing them only by average yield response can therefore be misleading. The appropriate comparison is whether an amendment reaches the affected depth, corrects the limiting process, avoids creating a new imbalance and remains affordable over the period in which benefits accrue.

4.1 Carbonate Liming

Ground limestone remains the reference intervention because the carbonate anion consumes acidity while calcium, or calcium plus magnesium in dolomite, replenishes exchangeable bases. When sufficient reactive material contacts the soil, aluminium activity declines and root conditions improve. Global syntheses support a positive average effect. One meta-analysis of field experiments found that liming increased soil pH, crop yield and profitability overall, with larger yield effects from incorporation than from surface placement and substantial variation by crop and rate (Enesi et al., 2023). Another world-wide meta-analysis found positive mean effects of multiple amendments and identified particularly strong responses in strongly acid, sandy, low-organic-matter soils, although comparison among materials was confounded by site selection, dose and cost (Zhang et al., 2023). The convergence supports lime as a core technology; it does not support a single global rate.

Lime requirement should be based on the acidity pool that must be neutralised to reach a crop-appropriate target. Buffer methods, incubation, titration and empirical regional equations differ in speed, calibration and soil range. A method calibrated for one mineralogy may be biased elsewhere, and laboratory fineness assumptions can diverge from the commercial product delivered to farms (Nguyen, 2023). Material quality should therefore be expressed through neutralising value, moisture, particle-size distribution and effective calcium carbonate equivalence or a locally equivalent measure. Fine particles react rapidly but can be dusty and difficult to spread; granulation improves handling but may slow dissolution if granules do not disperse. The nominal tonnes per hectare are meaningful only after correcting for quality.

Placement is equally important. Incorporation distributes carbonate through the tilled layer and increases soil-particle contact, which commonly produces a faster and larger response than surface spreading. No-till systems pose a trade-off: incorporation may disrupt structure and residue cover, whereas repeated surface application often creates a high-pH zone over an acid layer. Surface lime can move gradually through dissolution products, dissolved organic ligands and biopores, but movement is slow and soil-dependent. Column evidence indicates that combining lime with organic matter can move alkalinity deeper in some soils, yet adsorption of dissolved organic carbon and preferential flow strongly condition the result (Van Ryckel et al., 2025). Such mechanisms are promising but do not justify assuming rapid profile correction after a single surface application.

Crop response cannot be inferred from pH change alone. Long-term arable experiments show different yield-pH relations among cereals and other crops, with some species responding strongly and others weakly across the same pH range (Holland et al., 2019). Profitability likewise depends on crop sequence and the time over which residual benefits are valued. A 35-year economic analysis found that liming could improve gross margins but that benefits differed greatly by crop and that treatment differences accumulated over a long period (Holland & Behrendt, 2021). Lime should therefore be treated as a multi-year soil investment, with the cost allocated across its effective life rather than charged entirely to the first crop.

Overliming is a genuine management failure. Raising pH beyond the crop and soil target can reduce availability of micronutrients, promote calcium-phosphate precipitation, alter disease pressure and increase dispersion in some variable-charge soils. A high calcium input may also create or accentuate magnesium and potassium imbalance. Reviews of physical and chemical effects report generally positive outcomes but also inconsistent changes in bulk density, aggregation and nutrient availability across soils (Holland et al., 2018; Wenyika et al., 2025b). The safe principle is to correct the limiting acidity to a monitored target, not to maximise pH.

4.2 Gypsum and Soluble Calcium for Subsoil Constraints

Gypsum, $CaSO_4{\cdot}2H_2O$, is often described loosely as a liming material, but its principal function is different. It dissolves more readily than limestone and supplies calcium and sulphate that can move below the surface. Calcium can displace aluminium from exchange sites, improve root-cell function and reduce the activity of toxic aluminium species through sulphate complexes. Because sulphate does not neutralise protons as carbonate does, gypsum generally has little direct effect on reserve acidity. It is most defensible as a complement to lime where topsoil pH is corrected but low calcium or aluminium saturation constrains the subsoil.

The evidence is conditional rather than uniformly positive. A meta-analysis of no-till acid soils synthesised 129 harvests and 930 observation pairs and found a higher probability of cereal response where aluminium saturation in the 0.20-0.40 m layer exceeded 5%; water limitation also strengthened average response (De Castro Pias et al., 2020). Long-term field work in a subtropical no-till system found that surface-applied gypsum increased calcium and sulphate deeper in the profile and improved cumulative grain yield, while magnesium was more mobile than potassium (Caires et al., 2011). Other field evidence shows that rate, lime reactivity, rainfall and baseline subsoil chemistry alter outcomes (Fontoura et al., 2019). These findings argue against routine gypsum application based only on topsoil pH.

Potential costs include magnesium and, in some settings, potassium movement, sulphate leaching and an unjustified expense where subsoil calcium is already sufficient. Phosphogypsum or industrial gypsum sources may contain impurities that require regulatory and batch-specific testing. The decision should be based on depth-resolved exchangeable calcium, aluminium saturation, texture, drainage and expected water stress. Where deep incorporation of lime is feasible without unacceptable erosion or structural damage, it may address acidity more directly; where it is not, gypsum can improve the chemical rooting environment without being represented as a substitute for neutralisation.

4.3 Organic Amendments and Crop Residues

Manure, compost, green residues and crop residues can ameliorate acid soils through several pathways. Organic anions consume protons during decomposition, basic cations in ash replenish exchange sites, soluble and particulate organic matter complex aluminium, and nitrogen, phosphorus and sulphur may be supplied. Controlled studies and reviews show that residues can increase pH and reduce aluminium toxicity, but the effect depends on residue chemistry, rate, decomposition stage and soil buffering (Haynes & Mokolobate, 2001; Mokolobate & Haynes, 2002; Whalen et al., 2000). A high-ash, calcium-rich material may have a substantial liming value; a high-carbon residue with little alkalinity may immobilise nitrogen initially and produce only a transient pH response.

Organic materials should not be assigned a generic “lime equivalent” without analysis. Total carbon, carbon-to-nitrogen ratio, acid-neutralising capacity, soluble salts, nutrient content, moisture and contaminants determine agronomic value and transport cost. In pot and column experiments, large doses are often mixed uniformly with soil, conditions that overstate what can be achieved with limited farm biomass. Field supply is constrained by competing uses for fodder, fuel and bedding, and bulky materials are expensive to move. The strongest role is usually integrated: organic inputs improve nutrient cycling, aggregation and water relations while a calibrated mineral amendment provides predictable neutralisation.

The evidence also cautions against judging organics solely by pH. Comparative work found that plant benefit depended on the ability of an amendment to supply phosphorus and alleviate both aluminium and manganese toxicity, not on alkalinity alone (Lauricella et al., 2020). Manure or compost can raise pH yet increase nutrient loss if rates exceed crop demand. Immature compost, high salinity, pathogens, weed seeds and trace contaminants are additional risks. Quality assurance and nutrient budgeting are therefore part of acidity management, not separate concerns.

Crop-residue retention is especially valuable for prevention. Returning cations taken up by the crop reduces net alkalinity export, and lower nitrogen rates can reduce proton production and nitrate leaching. Long-term regional analysis in China found that residue return combined with nitrogen reduction alleviated cropland acidification relative to high-input practice (Zuo et al., 2023). Nevertheless, residues cannot be expected to reverse a large reserve-acidity pool quickly. Their contribution is best understood as maintaining the correction achieved by lime, supporting biological function and reducing the recurrence rate.

4.4 Biochar and Pyrogenic Amendments

Biochar is attractive because it can combine alkaline ash, persistent carbon, surface charge, porosity and nutrient retention. These properties are not intrinsic constants. Feedstock determines ash and nutrient composition; pyrolysis temperature alters pH, aromaticity and functional groups; post-production handling affects particle size and contamination; and ageing changes surface chemistry. Low-temperature crop-residue biochars have shown capacity to raise pH in acidic Ultisols, but the magnitude varies widely among residues (Yuan & Xu, 2011).

Meta-analyses demonstrate both potential and heterogeneity. Biochar has increased productivity on average, but effect size depends on soil pH, texture, climate, crop, dose and experimental setting (Biederman & Harpole, 2013; Liu et al., 2013). A global synthesis concluded that yield benefits were clearer in tropical than temperate agriculture, consistent with greater scope for liming and nutrient effects in low-fertility acid soils (Jeffery et al., 2017). Meta-analyses of phosphorus and nitrogen availability likewise show variable changes governed by feedstock, application rate and baseline nutrient status (Gao et al., 2019; Glaser & Lehr, 2019). These findings do not support applying any biochar to any acid soil; they support testing a characterised product against a diagnosed constraint.

Field evidence suggests that biochar can be most useful when it performs more than one function. In a tropical agricultural soil, biochar, compost and their combination improved several soil properties and maize performance, but treatment effects also reflected nutrient inputs and interactions rather than pure alkalinity (Agegnehu et al., 2016). A recent three-year peanut study reported that combined biochar and lime maintained higher pH, lowered exchangeable aluminium and improved yield stability relative to single treatments, with a favourable cumulative economic result under the study's local prices (Tu et al., 2025). This is useful evidence for complementarity, but it remains one crop, soil and cost structure and should not be generalised as proof that the combination is always synergistic.

Major barriers are cost, dose and product variability. Many field trials use tonnes per hectare, making feedstock supply, pyrolysis energy, transport and spreading decisive. A carbon benefit cannot be assumed without accounting for feedstock counterfactual, production emissions, stability and land-use effects. Some biochars contain excessive salts, polycyclic aromatic hydrocarbons or metals. Sustainable use therefore requires product standards, batch testing, realistic application rates and comparison with lower-cost lime and organic options. Biochar is best positioned as a multifunctional amendment where persistent carbon, nutrient retention or waste valorisation adds value beyond pH correction.

4.5 Phosphorus and Balanced Nutrient Management

Correcting acidity can reveal, rather than remove, nutrient limitation. Once root growth improves, crop demand for nitrogen, phosphorus, potassium and micronutrients increases. Phosphorus is the most consistent co-limitation in highly weathered soils. Applying phosphorus without reducing severe aluminium stress can produce low recovery because roots remain restricted and sorption is high; applying lime without phosphorus can produce an apparently disappointing yield response because the next limiting factor becomes dominant. This interaction explains why combined treatments often outperform single inputs in regional syntheses.

A 2025 meta-analysis of 30 experiments across 48 Ethiopian highland locations found the largest average yield response for lime plus phosphorus and substantial residual heterogeneity among practices and environments (Agumas et al., 2025). The numerical result is region-specific, but the causal lesson is broadly applicable: amendments should be evaluated within a complete nutrient programme. Phosphorus placement near the root zone, use of crop-appropriate rates, maintenance of organic matter and selection of efficient genotypes can reduce the total requirement. Excess phosphorus is not a remedy for fixation and creates water-quality risk.

Nitrogen management has a dual role. Adequate nitrogen is needed to capture the yield potential created by acidity correction, yet inefficient ammonium fertilisation and nitrate leaching drive future acidification. Split application, inhibitors where locally justified, legumes within balanced rotations, residue return and yield-targeted rates reduce this contradiction. Potassium, magnesium, sulphur, molybdenum and micronutrients should be assessed according to soil and tissue tests. The goal is not a universal “lime plus NPK” package but a balanced programme in which the amendment removes the diagnosed chemical barrier and fertilisation meets the crop's remaining demand.

4.6 Circular and Industrial Liming Materials

Industrial by-products, ash, shells and mineral residues can supply alkalinity and nutrients at lower purchase cost than quarried limestone, particularly near the source. Their sustainability depends on chemical composition, consistency, reactivity, transport distance and contaminant control. A product with high nominal calcium but coarse particles or low solubility may react too slowly; a highly reactive ash may increase pH rapidly but contain excessive potassium, salts, metals or caustic fractions. The label "waste-derived" is not evidence of circular benefit.

Each source should be tested for neutralising value, fineness, moisture, major nutrients, soluble salts and contaminants, and then field-calibrated. Regulations should distinguish agronomic use from waste disposal. The amendment rate must be based on effective neutralising capacity rather than mass, and nutrient contributions should be credited to avoid over-application. Where quality is variable, blending and certification may be more important than identifying another locally available material. Life-cycle benefit also declines when a low-value bulky product is transported over long distances.

Table 2 compares the main amendment classes by mechanism and best-fit context. The comparison shows that carbonate lime has the strongest and most transferable evidence for direct neutralisation, whereas gypsum, organic materials and biochar are complementary tools whose value rises when subsoil calcium, organic matter, nutrient retention or waste-management objectives are jointly important. No material is sustainable without diagnosis, quality assurance and monitoring.

Table 2. Comparison of principal amendment strategies for acid soils

Strategy	Primary function and best-fit context	Limitations and safeguards	Supporting references
Calcitic or dolomitic lime	Neutralises active and reserve acidity, reduces aluminium activity and supplies calcium; dolomitic material also supplies magnesium. Strongest evidence for diagnosed topsoil correction.	Response depends on effective neutralising value, fineness, incorporation, moisture, buffering and crop sensitivity. Excess can induce micronutrient or cation imbalance.	(Enesi et al., 2023; Holland et al., 2019; Zhang et al., 2023)
Gypsum	Supplies soluble calcium and sulphate and can improve the chemical rooting environment below a limed layer where subsoil calcium is low and aluminium is high.	Does not neutralise reserve acidity like carbonate. Benefits are heterogeneous; magnesium and potassium movement and impurity risks require monitoring.	(Caires et al., 2011; De Castro Pias et al., 2020; Fontoura et al., 2019)
Manure, compost and residues	Return basic cations, nutrients and carbon; organic ligands can complex aluminium and improve aggregation and water relations.	Alkalinity, nutrient release, carbon-to-nitrogen ratio, salinity, pathogens and contaminants vary. Bulky supply and competing uses limit feasible rates.	(Haynes & Mokolobate, 2001; Mokolobate & Haynes, 2002; Whalen et al., 2000)
Biochar	May combine alkaline ash, persistent carbon, surface charge and nutrient retention, especially in strongly acidic, weathered soils.	Feedstock, pyrolysis, dose and cost govern response. Salts, metals and organic contaminants require product standards and batch testing.	(Jeffery et al., 2017; Liu et al., 2013; Yuan & Xu, 2011)
Lime with organic or pyrogenic inputs	Can correct acidity while supplying nutrients, carbon and structural benefits; useful where constraints are genuinely co-limiting.	Apparent synergy may be additive nutrient and alkalinity effects. Factorial testing and nutrient crediting are needed to avoid excessive rates.	(Agegnehu et al., 2016; Agumas et al., 2025; Tu et al., 2025)
Circular or industrial materials	Potentially reduce disposal and purchase costs where a local source has verified neutralising capacity and nutrient value.	Composition, reactivity and contaminants may vary by batch. Certification, traceability and field calibration are prerequisites.	(Agegnehu et al., 2021; Fageria & Baligar, 2008)

Note. Effective neutralising value combines chemical neutralising capacity with particle-size reactivity. Gypsum should not be described as a liming material unless the specific product contains a verified acid-neutralising component

5. Biological Adaptation and Productive Utilisation

Chemical amendment is only one route to productivity on acid soils. Plants differ widely in sensitivity to aluminium, manganese, phosphorus deficiency and low calcium supply, and this variation can be used through crop choice, rotation design and breeding. Biological adaptation is most valuable when amendment is costly, acidity is spatially variable or residual subsoil constraints cannot be corrected rapidly. It should not, however, be represented as an alternative to diagnosis. A genotype described as acid tolerant may resist aluminium but remain sensitive to manganese, low phosphorus, drought or nutrient imbalance. Conversely, a crop that performs poorly at low pH may respond strongly once a modest amendment removes the dominant constraint. Productive utilisation therefore requires matching traits and species to the actual stress complex rather than selecting on pH alone (Kochian et al., 2015; Zhu & Shen, 2024).

The distinction between tolerance and sustainable utilisation is also important. Tolerant crops can produce acceptable yields while leaving reserve acidity, base-cation depletion and nutrient inefficiency unresolved. If harvested products and nitrate continue to export alkalinity, the soil may acidify further even while a tolerant cultivar masks the decline. Biological strategies are strongest when combined with maintenance liming, balanced nutrition, residue return and erosion control. They broaden the feasible management window, reduce the amendment needed to achieve a target yield and provide options for land that cannot be intensively tilled, but they do not make acidification chemically inconsequential.

5.1 Crop Selection, Breeding and Aluminium Resistance

Aluminium resistance is the best-characterised biological response to acid soils. Two broad mechanisms recur across crops. Exclusion mechanisms limit aluminium entry into the root apex, most commonly through root exudation of citrate, malate or oxalate that complexes Al^{3+} in the rhizosphere. Internal tolerance mechanisms bind, sequester or transport aluminium after uptake and protect sensitive cellular processes. Reviews of plant physiology and molecular genetics show that both classes can operate within a species and that expression is influenced by external pH, aluminium activity, phosphorus status and developmental stage (Bojórquez-Quintal et al., 2017; Kochian et al., 2015; Ma et al., 2001; Ryan et al., 2001).

The identification of aluminium-activated transporters created a direct route from mechanism to breeding. In wheat, the aluminium-activated malate transporter gene *TaALMT1* underpins an important resistance phenotype, while the multidrug and toxic compound extrusion gene *SbMATE* confers citrate-mediated tolerance in sorghum (Magalhaes et al., 2007; Sasaki et al., 2004). These discoveries are strong evidence that specific alleles can improve root growth under aluminium stress. Their agronomic value is nevertheless conditional. Nutrient-solution screening usually holds temperature, ionic composition and water supply constant, presents aluminium uniformly and measures early root traits. Field soils contain organic ligands, heterogeneous pH, phosphorus sorption, mechanical impedance, drought and multiple toxicities. A genotype ranking derived from hydroponics may therefore change in an Oxisol, Ultisol or acid sulphate soil.

Breeding programmes should use staged phenotyping: controlled screens for mechanism, soil-based assays for stress interactions, and multi-environment field trials with realistic amendment and fertiliser regimes. Yield stability, root distribution, nutrient-use efficiency and grain quality are more relevant endpoints than short-term root elongation alone. Marker-assisted or genomic selection can accelerate transfer of known resistance loci, but narrow dependence on a single exclusion mechanism may be vulnerable to variation in aluminium speciation or root-zone chemistry. Combining exclusion, internal detoxification, phosphorus efficiency and drought adaptation is likely to provide more durable performance than selecting for one laboratory trait.

Crop choice provides an immediate counterpart to breeding. Acid-tolerant cereals, forage grasses and legumes can be placed on more constrained fields, while sensitive high-value crops are allocated to zones where amendment can reliably reach the root profile. Lupins illustrate the opportunity and the caveat. Their phosphorus-acquisition traits and aluminium-adaptive mechanisms make them useful on some acidic, low-phosphorus soils, yet performance varies among species and cultivars and can be limited by waterlogging, disease or excessive manganese (Quiñones et al., 2022). The decision is thus agronomic and rotational rather than taxonomic: a nominally tolerant crop must fit climate, market, pest pressure and the intended contribution to soil fertility.

5.2 Phosphorus-Efficient Roots and Rhizosphere Adaptation

Phosphorus efficiency is central to productive utilisation because strong sorption by iron and aluminium oxides can maintain low solution phosphorus even after moderate liming. Plants acquire phosphorus through combinations of root length and fineness, root hairs, topsoil foraging, cluster roots, organic-anion exudation, phosphatase activity and associations with microorganisms. These traits differ in carbon cost and effectiveness according to phosphorus form, soil moisture and sorption capacity (Lambers et al., 2006). A larger root system is not automatically more efficient if aluminium inhibits the root apex or if phosphorus remains beyond the diffusion zone.

The rice protein kinase *PSTOL1* is a prominent example of a root-growth trait that improved performance under phosphorus deficiency (Gamuyao et al., 2012). Its discovery demonstrates the value of traditional germplasm and root architectural traits, but it does not establish a universal acid-soil solution. Low-phosphorus tolerance was the selected phenotype; soils with high aluminium saturation may require additional resistance mechanisms, and the benefit may depend on plant-available phosphorus and water. Root traits should therefore be evaluated in factorial combinations of acidity, phosphorus supply and moisture rather than in isolated low-phosphorus screens.

Rhizosphere acidification or alkalinisation can change nutrient availability over millimetres around roots. Uptake of ammonium, nitrate and cation-anion balance, proton release, bicarbonate release and organic-anion exudation all contribute (Hinsinger et al., 2003). These local processes can mobilise phosphorus or detoxify aluminium without measurably changing bulk-soil pH. They also complicate interpretation of soil tests: a bulk sample may underestimate the chemical environment experienced by an adapted root. Breeding and management should therefore connect root traits with spatially explicit measurements of aluminium activity, labile phosphorus and pH rather than infer mechanism from yield alone.

A sustainable strategy uses biological efficiency to improve recovery of a carefully limited phosphorus input, not to justify phosphorus mining. Phosphorus-efficient crops can reduce the fertiliser rate required for a given yield, but harvested phosphorus still has to be replaced. Localised placement may improve early uptake, whereas excessive band concentration can injure roots or intensify nutrient imbalance. Liming to a moderate, crop-specific target can reduce aluminium toxicity and increase root exploration, yet raising pH too far can shift phosphorus towards calcium-associated forms and induce micronutrient deficiencies (Penn & Camberato, 2019). The optimum is therefore a joint acidity-phosphorus target rather than maximum pH or maximum fertiliser rate.

5.3 Microbial and Mycorrhizal Strategies

Soil pH is a major organiser of microbial communities. Continental surveys and field gradients show strong changes in bacterial composition and in the balance between bacterial and fungal communities across pH ranges (Lauber et al., 2009; Rousk et al., 2010). Liming can consequently alter decomposition, nitrogen transformations, disease suppression and symbiosis as well as root chemistry. Recent reviews find frequent increases in microbial biomass or shifts towards bacterial activity after liming, but responses are not uniform and may reflect simultaneous changes in calcium, substrate supply and plant growth (Wenyika et al., 2025a). A higher microbial biomass is not by itself evidence of improved nutrient retention or lower greenhouse-gas loss.

Arbuscular mycorrhizal fungi, phosphorus-solubilising microorganisms and plant growth-promoting rhizobacteria may increase nutrient acquisition, modify root architecture or reduce stress. The mechanistic basis is credible, particularly where phosphorus diffusion and root exploration are limiting (Richardson et al., 2009). Field translation remains inconsistent because inoculants compete with resident communities and are exposed to acidity, temperature, moisture, pesticide residues and host specificity. Reviews of mycorrhizal deployment emphasise that greenhouse responses often exceed field responses and that benefits can disappear in fertile soil or under poorly matched host-fungus combinations (Thirkell et al., 2017).

Microbial products should therefore be evaluated as context-dependent biological inputs, not as replacements for amendment or fertiliser. Trials need an appropriate non-inoculated control, confirmation that the introduced organism established, measurement of indigenous community responses and testing across seasons. Product identity, viable propagule count, shelf life and contamination require quality control comparable to that expected for lime or fertiliser. Native inocula selected from acid soils may be better adapted than generic strains, but claims of tolerance must still be linked to reproducible crop outcomes. The most credible use is within an integrated root-zone environment in which severe aluminium toxicity has been reduced enough for the host and symbiont to function.

5.4 Pasture, Perennial and Agroforestry Options

Where annual cropping is marginal, perennial grasses, acid-adapted legumes, tree crops and agroforestry may provide more sustainable utilisation. Perennial roots protect the surface, capture nutrients from a larger soil volume and reduce the frequency of cultivation. Deep-rooted species may access water below an acidic layer if aluminium does not arrest root penetration. Legumes can supply biologically fixed nitrogen, although proton generation and nitrate loss mean that legume-based systems are not automatically neutral with respect to acidification (Bolan et al., 1991). Removal of hay, timber or fruit also exports basic cations, so maintenance inputs remain necessary.

Species mixtures can distribute risk and exploit complementary rooting depths, but establishment is often the most acidity-sensitive phase. Strategic banding or spot application of lime and phosphorus can create establishment zones at lower cost than whole-field treatment. Once cover develops, residue return and reduced erosion help retain alkalinity and organic matter. The evidence base is less standardised than for annual crop liming: studies use different species, grazing intensities, soil depths and production endpoints, and long-term comparisons of amendment, pasture renovation and agroforestry are scarce. Management should therefore use local adaptation trials and monitor botanical composition, ground cover, nutrient export and acidification rather than assume that perenniality alone is protective.

Productive utilisation must also respect land-use boundaries. Many intact forests, savannas, wetlands and peat-forming systems occur on acid soils and support biodiversity, water regulation and carbon storage precisely because they have not been converted to intensive agriculture. The presence of a technically manageable acidity constraint is not an argument for clearing these ecosystems. Investment should prioritise already-cleared, degraded or underperforming agricultural land, where restoration of soil function can reduce pressure for expansion. Table 3 summarises biological options as complements to chemical correction and makes explicit where evidence is mechanistically strong but field generalisability remains limited.

Table 3. Biological options for productive utilisation of acid soils

Biological option	Functional basis and appropriate use	Evidence limitation or management caveat	Supporting references
Aluminium exclusion in cereals	Organic-anion efflux protects root apices; examples include *TaALMT1* in *Triticum aestivum* and *SbMATE* in *Sorghum bicolor*. Useful for partial correction or residual subsoil stress.	Nutrient-solution ranking may change under field heterogeneity, drought, phosphorus deficiency or manganese toxicity.	(Magalhaes et al., 2007; Sasaki et al., 2004)
Internal aluminium tolerance	Sequestration, transport and cellular protection complement exclusion and may broaden resistance across root tissues.	Mechanisms are often inferred from controlled systems; durable yield advantage requires multi-environment confirmation.	(Kochian et al., 2015; Zhu & Shen, 2024)
Phosphorus-efficient roots	Root architecture, hairs, organic-anion release and *PSTOL1*-associated growth can improve phosphorus acquisition; relevant to *Oryza sativa* and other crops on sorbing soils.	Low-phosphorus tolerance is not equivalent to aluminium resistance and does not replace phosphorus removed in harvest.	(Gamuyao et al., 2012; Lambers et al., 2006)
Acid-adapted legumes and lupins	*Lupinus* spp. and selected legumes can combine adaptation, phosphorus acquisition and rotational nitrogen inputs.	Species and cultivar responses vary; waterlogging, disease, manganese and net system acidification can remain limiting.	(Bolan et al., 1991; Quiñones et al., 2022)

Biological option	Functional basis and appropriate use	Evidence limitation or management caveat	Supporting references
Mycorrhizal and bacterial inoculants	Potential improvement of nutrient acquisition, stress tolerance and root growth where host, strain and soil conditions are compatible.	Establishment, resident-community competition, product viability and field consistency are frequently under-reported.	(Richardson et al., 2009; Thirkell et al., 2017)
Perennial, pasture and agroforestry systems	Persistent cover, deeper roots and lower disturbance can reduce erosion and use land unsuited to intensive annual cropping.	Establishment may require localised correction; nutrient export and acidification continue. Intact acid-soil ecosystems should not be converted.	(Agegnehu et al., 2021; Fageria & Baligar, 2008)

Note. Gene symbols are italicised; protein names are not. Biological options are complements to, rather than universal substitutes for, chemical correction and balanced nutrition

6. Integrated Soil-Acidity Management Across Scales

Sustainable management is a sequence of linked decisions rather than a choice among isolated products. The sequence begins with diagnosis, identifies the crop and depth that matter, separates corrective from maintenance actions, and evaluates whether an input can be sourced, applied and monitored at acceptable cost. Integration is necessary because acidity interacts with nutrient deficiency, water stress, compaction, erosion, crop genetics and farm resource constraints. Treating the pH value as the whole problem produces two common errors: under-application where reserve acidity is large and over-application where a sensitive crop response is actually caused by another limitation.

Integrated soil fertility management provides a useful organising principle because it combines mineral inputs, organic resources, adapted germplasm and local agronomic knowledge rather than assigning universal superiority to any single input (Vanlauwe et al., 2010). Applied to acid soils, the principle requires an additional depth dimension. A topsoil can be corrected while the subsoil remains toxic, and a small surface sample can conceal the zone that limits rooting during drought. The management unit may also be smaller than the field where erosion, parent material or historical fertiliser placement creates strong spatial variation.

6.1 Diagnosis and Site-Specific Targets

A minimum diagnosis should include pH measured by a specified method, texture, organic carbon or matter, exchangeable calcium and magnesium, a measure of exchangeable acidity or aluminium, available phosphorus and relevant crop history. Buffer pH or a calibrated lime-requirement test is preferable when reserve acidity is important. Sampling by depth is essential where subsoil acidity is suspected, especially in long-term no-till, perennial systems and highly weathered profiles (Hettithanthri et al., 2026; Nguyen, 2023). The sampling design should capture management zones rather than average them indiscriminately.

Targets should be defined in relation to crop response and soil buffering, not as a universal pH number. For some tolerant crops, reducing aluminium saturation below a damaging threshold may be more economical than raising the entire soil to near-neutral pH. Legumes dependent on nodulation or crops sensitive to manganese may require a different target. Dolomitic material is appropriate where magnesium is deficient, but unnecessary use can distort calcium-magnesium balance. The target must also specify the depth and time horizon: a surface pH target for seedling establishment is different from a profile target for perennial roots.

Diagnostic uncertainty should be managed explicitly. Soil tests are operational measurements, and results vary with extractant, soil-to-solution ratio, season and laboratory method. Apparent changes in pH after amendment may partly reflect moisture or salt effects. Crop symptoms are likewise non-specific. A defensible recommendation triangulates laboratory results, field history, root observations and crop response. Where evidence remains uncertain, a replicated strip or small-plot test can reduce the risk of whole-field investment. Site-specific management is therefore an experimental discipline as well as a mapping exercise.

6.2 Combination, Sequencing and Placement

The first corrective decision is whether the principal constraint lies in the cultivated layer, below it or across the profile. Finely ground carbonate incorporated into the target layer is the most predictable treatment for topsoil acidity. In no-till or established perennial systems, surface application preserves soil structure and residue cover but reacts gradually downward. Gypsum may be added where exchangeable calcium is low and aluminium toxicity occurs below the limed layer; the evidence does not support routine use on every acid soil (De Castro Pias et al., 2020; Fontoura et al., 2019). Deep placement or mechanical incorporation can accelerate correction but must be weighed against erosion, fuel use and structural damage.

Nutrients should be sequenced with amendment according to the limiting process. Severe aluminium stress may need correction before a crop can exploit phosphorus, while modest acidity and strong phosphorus deficiency may justify simultaneous banding. Organic inputs can be applied to improve aggregation, nutrient retention and biological activity, but their nutrient content should be subtracted from fertiliser requirements. Biochar is most defensible where a characterised product supplies a persistent function not obtained economically from lime or compost. The relevant comparison is the complete package per unit of sustained yield, not the price or pH effect of an individual material.

Combination does not guarantee synergy. Additive effects can be mistaken for interaction when lime supplies alkalinity and manure supplies phosphorus. High rates of both may overshoot the target, raise salinity or increase nutrient loss. Factorial field trials are needed to distinguish interaction from parallel correction of different constraints. Recent meta-analysis found large average yield gains from amendments in acid soils, but heterogeneity remained substantial across climate, soil, crop and treatment characteristics (Zhang et al., 2023). This variability argues for calibrated packages and adaptive monitoring rather than fixed recipes.

Placement can reduce cost and environmental exposure. Banded lime or pelleted material near a seed row may create a favourable microsite, while whole-field application addresses a broader reserve-acidity pool. Spot treatment can help establish trees or perennial forage. These approaches should not be described as full reclamation when untreated soil continues to constrain later root expansion. The choice depends on the spatial scale of the root system, amendment reactivity, machinery and expected persistence. Table 4 translates these principles into decision contexts and monitoring triggers.

6.3 Monitoring, Maintenance and Prevention of Re-acidification

Correction is temporary if the processes that caused acidification continue. Monitoring should use consistent sampling depth, season and analytical method, and should follow both chemistry and crop response. Surface pH alone is insufficient after repeated surface liming because it can remain favourable while acidity advances below the sampled layer. Exchangeable aluminium, calcium and magnesium, crop tissue composition, rooting depth and yield stability provide a stronger basis for maintenance decisions. The interval between tests should reflect buffering capacity, nitrogen input, rainfall, crop removal and amendment history rather than a fixed calendar.

Maintenance management aims to replace alkalinity exported or consumed before severe toxicity returns. Nitrogen source and rate are central. Matching supply to crop demand, splitting applications and retaining nitrate within the rooting zone reduce proton generation associated with leaching. Crop residues return base cations and should be retained where competing uses do not outweigh soil costs. Erosion control is equally important because loss of nutrient-rich surface soil exposes more acidic subsoil and removes previously applied amendment. Cover crops, contour measures, reduced bare fallow and controlled grazing can therefore protect the chemical investment.

Threshold-based maintenance is preferable to crisis response. Waiting for visible symptoms sacrifices yield and may require a larger corrective dose; applying lime routinely without testing wastes material and can induce imbalance. Long-term experiments demonstrate that economic return depends on starting pH, crop sequence, yield value and the persistence of amendment effects (Holland & Behrendt, 2021). Farm records should therefore link lime source, neutralising value, application date, placement, soil-test trajectory and yield. This creates local response functions that become more useful than generic recommendations over successive cycles.

Table 4. Profile-based decision framework for integrated acid-soil management

Decision context	Integrated response and placement	Monitoring trigger and principal caveat	Supporting references
Surface acidity with adequate subsoil calcium	Apply quality-assured carbonate to the cultivated layer at a calibrated rate; incorporate where agronomically and physically appropriate.	Repeat consistent topsoil tests and track crop response. Avoid routine gypsum or a fixed pH target.	(Enesi et al., 2023; Nguyen, 2023)
Acidic, calcium-poor subsoil	Correct the surface layer and consider gypsum, deep placement or tolerant roots according to aluminium, calcium, texture and water regime.	Monitor subsoil calcium, aluminium, magnesium, potassium and root depth. Gypsum response is not universal.	(De Castro Pias et al., 2020; Hettithanthri et al., 2026)
Strong acidity plus phosphorus deficiency	Sequence or co-apply lime and crop-appropriate phosphorus; use placement and adapted germplasm to improve recovery.	Track yield and nutrient recovery, not pH alone. Excess phosphorus creates cost and water-quality risk.	(Agumas et al., 2025; Penn & Camberato, 2019)
Rapid re-acidification under high nitrogen input	Correct acidity while improving nitrogen-use efficiency, retaining residues and replacing exported alkalinity.	Use nitrogen balance, nitrate risk and profile pH trends to trigger maintenance rather than waiting for symptoms.	(Guo et al., 2010; Tian & Niu, 2015; Zuo et al., 2023)
Resource-constrained smallholder system	Prioritise responsive fields, calibrated micro-zones or shared application services; combine amendment with essential nutrients and adapted crops.	Evaluate delivered cost, quality, tenure and access. A low purchase price can conceal labour or transport burdens.	(Oumer et al., 2023; Silva et al., 2025; Vanlauwe et al., 2010)
No-till, perennial or erosion-prone land	Favour surface application, localised establishment zones or low-disturbance placement; protect residue cover and structure.	Expect slower depth response and monitor chemical stratification. Deep tillage may impose erosion and fuel costs.	(Fontoura et al., 2019; Holland et al., 2018)

Note. The framework is conditional and non-exhaustive. Treatment thresholds must use locally calibrated analytical methods and crop-specific response information

6.4 Economics, Access, Extension and Policy

The agronomic optimum is not necessarily the economically feasible rate. Lime is bulky and low in unit value, so quarry location, road condition, particle size, moisture, transport and spreading often dominate delivered cost. Smallholders may face minimum purchase quantities, uncertain quality, limited credit and weak demand aggregation. Analysis of the Ethiopian lime value chain found inefficiencies in production, distribution and coordination that constrained use even where the agronomic need was recognised (Oumer et al., 2023). These barriers cannot be solved by field recommendations alone.

Recent spatial-economic analysis for sub-Saharan Africa argues that soil-acidity remediation requires targeted investment rather than uniform promotion (Silva et al., 2025). The implication is not that only high-potential zones deserve support. It is that public expenditure should distinguish areas where lime supply, crop response, market access and complementary nutrients can produce durable benefits from areas where transport cost or water limitation makes another land use more rational. Geospatial targeting must be combined with field validation because continental soil maps cannot replace plot-scale measurements.

Policy has four linked roles. Standards and labelling should report effective neutralising value, fineness, moisture and relevant contaminants. Infrastructure and producer organisation can lower transaction and transport costs. Credit or subsidy design should support quality-assured, diagnosed use rather than tonnage distributed, and should avoid crowding out local markets once supply chains mature. Extension should communicate that gypsum, biochar and organic materials have distinct functions and that visible pH change is not the only outcome. Demonstrations need untreated and economically relevant comparator treatments, not only a promoted package.

Distributional effects require attention. Tenant farmers may not capture the residual benefit of lime, while women and resource-poor farmers may have less access to bulk transport, machinery or credit. Community spreading services, smaller certified packages and shared soil testing can lower entry barriers, but their costs and governance must be assessed. Local materials may reduce cash expense yet still impose labour burdens or contamination risk. A sustainable programme therefore evaluates who pays, who controls the input, who receives the residual benefit and whether adoption persists after project support ends.

7. Environmental Trade-offs and Safeguards

Acid-soil correction can improve resource-use efficiency and reduce pressure to cultivate additional land, but it is not environmentally neutral. Quarrying, grinding and transporting limestone consume energy; carbonate reactions can release carbon dioxide; improved nitrogen cycling can increase or decrease nitrous oxide; and greater biomass can change soil carbon inputs. Amendment can also alter dissolved carbon, nitrate, sulphate, base-cation and metal movement. The appropriate comparison is therefore between complete management pathways over time, including the consequences of leaving acidity untreated, rather than between an amended and an abstract zero-impact soil.

7.1 Carbon and Greenhouse-Gas Accounting

Agricultural lime enters greenhouse-gas inventories because carbonate dissolution can release carbon dioxide. Field-scale net emissions depend on limestone composition, dissolution products, drainage, incorporation, transport and the fate of bicarbonate. A United States analysis showed that gross carbonate application should not be equated mechanically with net atmospheric emission because dissolution and transport pathways alter the balance (West & McBride, 2005). Nevertheless, the existence of uncertainty is not a basis for assigning zero emissions. Product-specific life-cycle assessment should include extraction, grinding, haulage, spreading and direct soil fluxes.

Liming can also modify nitrous oxide, methane and soil organic carbon. A global synthesis reported potential co-benefits for food production and climate mitigation, but effects varied among greenhouse gases and contexts (Wang et al., 2021). A more recent global meta-analysis associated mitigation of acidification with improved soil quality, yield, farm returns and lower greenhouse-gas emission intensity under some management combinations (Xu et al., 2025). Such averages are informative but cannot establish that every liming event is climate-beneficial. Higher yield may reduce emissions per unit product while total field emissions remain unchanged or increase, and short experiments may not capture carbonate dissolution or long-term carbon turnover.

The effect on soil organic carbon is similarly conditional. Liming may increase plant inputs and aggregation, but it can also stimulate decomposition by relieving microbial acidity stress. A critical review found no universal direction of net soil-carbon change across studies (Paradelo et al., 2015). Acidification itself can deplete soil inorganic carbon in calcareous and transitional systems, creating an overlooked carbon loss pathway (Raza et al., 2021). Climate appraisal should therefore report separate stocks and fluxes, specify the time horizon and distinguish area-based from product-based metrics. Claims of carbon neutrality require a full balance, not a single soil-carbon measurement.

7.2 Nutrient Loss, Water Quality and Soil Physical Risk

Raising pH and stimulating mineralisation can increase the pool of mobile nitrate and dissolved organic matter. In a double-cropped rice system, liming promoted carbon and nitrogen leaching, demonstrating that chemical correction can create off-site losses where water flux and nutrient supply are high (Tang et al., 2025). Laboratory and field evidence also indicates that dissolved organic carbon can carry alkalinity downward from limed layers, with transport governed by adsorption and soil structure (Van Ryckel et al., 2025). Downward movement may help subsoil chemistry, but leached nitrogen or carbon reaching drainage water is not an agronomic benefit.

Gypsum introduces soluble calcium and sulphate and can displace magnesium or potassium from exchange sites. In coarse soils or high-rainfall environments, this creates a risk of nutrient movement below effective roots. Phosphorus loss can increase if manure or fertiliser exceeds crop demand, even when liming improves phosphorus availability. Monitoring should therefore include nutrient balance and, where risk is high, drainage or water-quality indicators. Rates should be split or reduced when crop uptake cannot match mineralisation, and amendment should not be applied immediately before intense rainfall on vulnerable slopes.

Physical risks depend on the placement method. Deep ripping or incorporation may improve amendment contact and break a compact layer, but repeated disturbance can damage structure and increase erosion. Surface application under no-till preserves cover yet may create steep chemical stratification. Fine dry lime can create dust exposure and drift, while wet materials increase transport mass and compaction risk. Sustainability requires matching application technology to soil moisture, slope and residue cover, with worker protection and calibrated spreading. These operational factors are often absent from efficacy trials but can determine the real environmental outcome.

7.3 Biodiversity, Contaminants and Overliming

Liming changes habitat as well as chemistry. In agricultural soils, moderate correction can increase earthworm activity, microbial biomass and crop-root growth, but the direction and desirability of biodiversity change depend on the starting ecosystem (Holland et al., 2018; Wenyika et al., 2025a). Acid-adapted organisms may decline when pH is raised, and liming semi-natural grasslands, heathlands or forests can erode conservation value. The objective in cropland is functional recovery within a production system, not universal maximisation of pH or bacterial dominance.

Overliming can reduce availability of iron, manganese, zinc, copper and boron, induce magnesium-potassium or calcium-magnesium imbalance, alter phosphorus forms and suppress acid-adapted crop traits. The risk is greatest where recommendations ignore buffering, use uncalibrated local material or repeat applications before the previous dose has reacted. A crop response plateau is a warning against chasing a higher pH. Maintenance should be triggered by measured decline and crop need rather than by a belief that more neutral soil is always better.

Alternative amendments introduce additional quality concerns. Industrial by-products may contain cadmium, lead, chromium, fluorine or excessive salts; sewage-derived materials can contain organic contaminants or pathogens; biochar quality varies with feedstock and pyrolysis. Regulatory approval should be based on total and bioavailable contaminants, leaching behaviour, application rate and cumulative loading. Batch certification and traceability are essential when composition is variable. Waste diversion is environmentally favourable only when the material performs a legitimate agronomic function and does not transfer a disposal problem to agricultural land.

7.4 Sustainability Appraisal and Land-Use Boundaries

A sustainability appraisal should integrate agronomic response, amendment persistence, input supply, farmer cost, greenhouse-gas balance, nutrient loss, biodiversity and land-use consequence. These dimensions can move in opposite directions. A high lime rate may maximise short-term yield but reduce return on investment, increase transport emissions and induce micronutrient deficiency. A low rate may be affordable yet fail to reach subsoil roots. Biochar may store persistent carbon but be uneconomic at the dose used in an experiment. A tolerant crop may reduce input demand but provide a lower market return. Transparent appraisal makes these trade-offs explicit rather than collapsing them into a single label of “sustainable”.

The counterfactual matters. Restoring an already-cleared acid field may increase production with less ecological damage than expanding into forest, while intensive treatment of remote marginal land may have a larger footprint than supporting perennial cover or non-crop ecosystem services. Decisions should consider the opportunity cost of amendment and the value of leaving some acid soils unconverted. National programmes also need safeguards against using yield-improvement potential to legitimise land clearing. Soil rehabilitation and habitat conservation are complementary only when land-use boundaries are explicit.

Table 5 consolidates the main trade-offs and safeguards. It shows that most risks can be reduced through diagnosis, quality assurance, nutrient budgeting, life-cycle accounting and land-use planning, but none can be eliminated by amendment choice alone. Sustainable acid-soil management is therefore an accountable process with measurable thresholds, not a claim attached to a material.

Table 5. Environmental and social trade-offs in acid-soil remediation

Trade-off	Mechanism and risk condition	Safeguard or indicator	Supporting references
Carbon dioxide from limestone supply and reaction	Quarrying, grinding, transport and carbonate dissolution create emissions; net release depends on chemistry, drainage and accounting boundary.	Report product composition, transport and direct fluxes separately and use both area- and product-based metrics.	(Wang et al., 2021; West & McBride, 2005)
Soil carbon and non-carbon-dioxide greenhouse gases	Yield and residue inputs may increase, while microbial decomposition and nitrous oxide can also change. Direction is context-dependent.	Measure soil organic and inorganic carbon and greenhouse gases over an adequate time horizon.	(Paradelo et al., 2015; Raza et al., 2021; Xu et al., 2025)
Carbon and nitrogen leaching	Higher pH, mineralisation and dissolved organic matter movement can increase mobile carbon or nitrate under strong drainage.	Use nutrient budgets, timing, drainage monitoring and rates matched to crop uptake.	(Tang et al., 2025; Van Ryckel et al., 2025)
Base-cation and micronutrient imbalance	Gypsum can move magnesium or potassium; excessive lime can reduce micronutrient availability or alter phosphorus forms.	Monitor exchangeable cations and tissue status and stop at the crop-specific response target.	(De Castro Pias et al., 2020; Penn & Camberato, 2019)
Contaminants and variable amendment quality	By-products, composts and biochars can contain salts, metals, pathogens or organic contaminants, with cumulative loading risk.	Require batch certification, traceability, contaminant limits and application-rate accounting.	(Lauricella et al., 2020; Yuan & Xu, 2011)
Biodiversity and land-use change	Liming shifts acid-adapted communities; productivity gains can either reduce expansion pressure or encourage conversion of intact ecosystems.	Restrict remediation programmes to appropriate agricultural land and include conservation and tenure safeguards.	(Holland et al., 2018; Wenyika et al., 2025a)

Note. A favourable change in one indicator does not establish overall sustainability. Appraisal should compare complete management pathways against an explicit land-use counterfactual

8. Future Directions

The immediate research priority is to replace short, topsoil-centred efficacy trials with long-term, depth-resolved field experiments. Treatments should separate amendment type, effective neutralising dose, particle size, placement, phosphorus supply, organic input and genotype so that interaction can be distinguished from the additive correction of different constraints. Repeated measurements should include pH by a specified method, exchangeable aluminium and bases, reserve acidity, root distribution, nutrient recovery, yield stability, water use, greenhouse gases, leaching and whole-farm cost. Trials need sufficient duration to observe reaction, residual benefit and re-acidification, particularly in no-till and perennial systems where downward movement is slow (Hettithanthri et al., 2026; Holland et al., 2019).

Subsoil acidity requires dedicated experimental designs. Surface and subsurface samples should be linked to root imaging or excavation and to seasonal water extraction. Comparisons of surface lime, incorporated lime, gypsum, deep placement and tolerant germplasm should use common endpoints and realistic machinery. Research should identify the combinations of texture, rainfall, aluminium saturation and calcium status under which soluble calcium produces a reliable yield benefit, thereby narrowing the broad heterogeneity found in gypsum syntheses (De Castro Pias et al., 2020). Development of less disruptive placement methods is a parallel engineering priority.

Amendment-quality research should move from nominal material classes to measured properties. Lime studies need effective neutralising value and size distribution; organic-amendment studies need alkalinity, nutrient release and contaminant data; biochar studies need feedstock, temperature, ash, surface properties, stability and production emissions. Dose should be expressed both as mass and functional input. Comparable characterisation would make meta-analysis more explanatory and prevent attribution of a response to "biochar" or "compost" when the operative factor was nutrient addition or alkalinity (Gao et al., 2019; Zhang et al., 2023).

Biological research should connect molecular mechanisms with field performance. Aluminium-resistance genes and phosphorus-efficient root traits should be tested across soil types, nutrient regimes, drought and disease pressure, using yield and nutrient-use outcomes over multiple seasons (Gamuyao et al., 2012; Kochian et al., 2015). Microbial inoculant studies should confirm strain persistence, quantify resident-community change and report product viability. Breeding targets should include maintenance of performance under partial, economically feasible correction rather than only survival under extreme stress. This would position genetics as a means of lowering amendment demand without normalising progressive soil degradation.

Environmental accounting needs harmonised boundaries. Studies should report quarrying and transport assumptions, direct carbonate carbon dioxide, nitrous oxide and methane fluxes, soil organic and inorganic carbon, and nutrient losses over a stated time horizon. Results should be expressed per hectare and per unit of usable product to distinguish absolute from intensity effects. Long-term field data are needed to test the net mitigation suggested by global syntheses and to identify conditions in which leaching or stimulated decomposition offsets benefits (Tang et al., 2025; Wang et al., 2021; Xu et al., 2025).

Implementation research is equally urgent. Delivered cost, product quality, labour, tenure, credit, gendered access, extension quality and residual benefit should be measured alongside yield. Randomised or quasi-experimental evaluations of transport support, community spreading, vouchers, quality certification and soil-testing services could identify which policy instruments produce sustained, correctly targeted adoption. Spatial models should be validated against field response and supply-chain reality before guiding investment (Oumer et al., 2023; Silva et al., 2025). The longer-term objective is an adaptive decision system that links profile-scale diagnosis, crop and trait choice, material quality, economic thresholds and environmental safeguards while preserving a clear boundary against conversion of intact acid-soil ecosystems.

9. Conclusions

Acid soils are not defined adequately by a low pH reading. Their productive constraint emerges from the depth-specific interaction of active and reserve acidity, aluminium and manganese toxicity, base-cation depletion, phosphorus sorption, root restriction, water supply and biological response. The most reliable evidence supports liming when the material is quality-assured, the rate is based on soil buffering and crop sensitivity, and the amendment reaches the soil layer that limits roots. Average yield responses from syntheses are useful for demonstrating potential, but they should not be converted into universal rates or pH targets because variation among soils, crops, climates, placement methods and co-limiting nutrients is substantial.

Gypsum, organic resources and biochar have legitimate but narrower functions. Gypsum can improve calcium supply and reduce aluminium activity below a limed layer, yet it does not neutralise reserve acidity and may move magnesium or potassium. Organic amendments can complex aluminium, return basic cations and improve structure, but their alkalinity, nutrient release and contaminants vary. Biochar can add persistent carbon and nutrient-retention functions in selected settings, particularly strongly acidic, highly weathered soils, but product characterisation, dose, cost and life-cycle performance determine whether it is preferable to simpler alternatives. None of these materials should be promoted by category name without chemical and agronomic evidence.

Biological adaptation extends the range of feasible management. Aluminium-resistance mechanisms, phosphorus-efficient roots, acid-adapted crops and selected symbioses can improve establishment and resource capture under partial correction. Their strongest role is complementary: they lower risk and amendment demand while balanced nutrition, residue return and maintenance liming prevent continued degradation. Mechanistic success in nutrient solution or controlled substrate does not establish field effectiveness, and genotype or inoculant recommendations require multi-environment validation.

A defensible management pathway begins with profile-based diagnosis, defines a crop- and depth-specific target, selects an amendment by function and effective neutralising value, corrects nutrient imbalance, uses adapted germplasm and protects the corrected soil from erosion and renewed acidification. Monitoring must retain consistent sampling depths and methods and should include exchangeable aluminium and bases, root performance, tissue status, yield stability and nutrient balance rather than pH alone. Economic feasibility depends heavily on transport, quality control, tenure and access to complementary inputs, making supply-chain and extension design integral to soil management.

Sustainability cannot be inferred from yield improvement. Quarrying, transport, direct carbonate emissions, greenhouse-gas responses, carbon stocks, nutrient leaching, biodiversity, contaminant loading and land-use change must be assessed against a credible counterfactual. Productive investment should prioritise already-cleared and degraded agricultural land. Intact forests, wetlands, savannas and other acid-soil ecosystems should not be treated as unused land merely because agronomic correction is technically possible. The central conclusion is therefore conditional but robust: acid soils can support sustained production when chemical correction, biological adaptation, nutrient management, economic access and environmental safeguards are designed as one monitored system.

10. Limitations

As a critical narrative review, this synthesis is intrinsically vulnerable to selection and interpretive bias despite a transparent search, explicit eligibility criteria and structured appraisal. The accessible search environment did not provide complete coverage of every subscription bibliographic database, and the review was limited to English-language sources with verifiable bibliographic metadata and sufficient accessible information for claim checking. Consequently, relevant regional studies, theses or older non-English evidence may have been missed, particularly from countries where acid-soil management is important but international indexing is uneven.

The evidence base is highly heterogeneous. Studies differ in pH method, soil depth, acidity threshold, amendment characterisation, rate expression, crop, climate, duration and outcome reporting. Pot and nutrient-solution experiments often provide strong mechanistic control but limited field generalisability, whereas field experiments may confound acidity correction with nutrient supply, water conditions or management history. Meta-analyses improve statistical power but inherit these differences and are vulnerable to publication bias and incomplete reporting. The review therefore did not attempt a new quantitative synthesis or formal risk-of-bias score.

Long-term evidence remains uneven for subsoil correction, combined amendments, microbial inoculants, greenhouse-gas balance, contaminant accumulation and farmer-level distributional effects. Economic conclusions are sensitive to local prices, transport, tenure and residual benefits and cannot be transferred directly among regions. Environmental outcomes also depend on the counterfactual land use and the accounting boundary. These limitations mean that the integrated framework should guide diagnosis and adaptive testing rather than serve as a fixed prescription. Conclusions were restricted to relationships supported across multiple evidence types, while newer or context-specific findings were treated as provisional.

Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

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

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