

The Role of Soil pH in Plant Mineral Nutrition: A Review

Waizah, Y* & Angyu M. D.

Department of Soil Science and Land Resources Management, Federal University Wukari, Taraba State, Nigeria.

*Corresponding author: waizahyakub@gmail.com

ABSTRACT

Soil pH is a fundamental determinant of soil fertility, nutrient dynamics, and crop productivity, often regarded as the master variable governing soil chemical, biological and physical processes. It regulates the solubility, availability and balance of essential plant nutrients, while also influencing microbial activity and the behavior of toxic elements. This review synthesizes current understanding of how soil pH interacts with nutrient availability, microbial activity and plant physiological responses to shape crop performance across diverse agroecosystems. It highlights the adaptive strategies of plants to tolerate pH extremes, including root morphological changes, rhizosphere acidification, ion homeostasis and symbiotic associations with microorganisms. Furthermore, the paper discusses soil management approaches such as liming, application of acidifying agents, organic matter incorporation, balanced fertilization and the cultivation of pH-resilient crop varieties. Integrated soil pH management, supported by continuous soil testing and precision monitoring, emerges as a sustainable framework for maintaining nutrient balance, minimizing toxicity and enhancing soil biological health. The review underscores that effective pH regulation is essential not only for optimizing nutrient uptake and improving crop yields but also for ensuring the long-term resilience and sustainability of agricultural systems in the face of climate and land-use pressures.

Keywords: Soil pH, nutrient availability, microbial activity, plant adaptation, soil fertility management, sustainable agriculture

INTRODUCTION

Soil pH is one of the most critical properties influencing plant growth and crop productivity. It refers to the measures of hydrogen ion concentration in the soil solution and serves as a master variable that governs numerous soil processes, particularly those related to nutrient solubility and plant mineral nutrition (Brady and Weil, 2017). Soil fertility is a cornerstone of agricultural productivity, and its maintenance is central to ensuring global food security. Among the many properties that determine soil fertility, soil pH stands out as one of the most fundamental and influential (Kabata-Pendias and Mukherjee, 2021). Although it is straightforward to define, soil pH has complex and far-reaching effects on soil chemistry, biology, and plant physiology, which justifies its classification as the master variable of soil fertility (Marschner, 2012).

The significance of soil pH lies in its ability to regulate the solubility, availability and balance of mineral nutrients. Plant nutrition depends on the adequate supply of essential macronutrients such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) as well as micronutrients like iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), and molybdenum (Mo). The availability of these elements is not constant but is strongly influenced by the chemical environment of the soil solution, which is largely dictated by pH. For instance, in strongly acidic soils, phosphorus is fixed by aluminum (Al^{3+}) and iron (Fe^{3+}) compounds, rendering it unavailable to plants, while in alkaline soils, phosphorus precipitates with calcium (Ca^{2+}), similarly limiting its solubility (Shen *et al.*, 2011). Micronutrients like Fe, Zn, and Mn are abundant under acidic conditions but tend to become deficient under alkaline conditions due to precipitation and reduced solubility (Kabata-Pendias and Mukherjee, 2021). These nutrient-pH relationships underscore the critical role soil pH plays in balancing plant mineral nutrition.

The global distribution of soil pH further illustrates its agricultural importance. Acidic soils, defined as those with a pH below 5.5, dominate much of the humid tropics, where high rainfall leads to leaching of basic cations and the accumulation of exchangeable aluminium. It is estimated that acid soils cover nearly 30% of the world's ice-free land surface and support a significant proportion of the global population, particularly in Latin America, Africa, and Southeast Asia (Fageria and Baligar, 2023). These soils pose unique challenges, including aluminium and manganese toxicity, calcium and magnesium deficiencies, and reduced microbial activity. Conversely, alkaline soils, common in arid and semi-arid regions, are characterized by high concentrations of carbonates and bicarbonates, which result in deficiencies of essential micronutrients such as Fe and Zn. Calcareous soils, in particular, account for over 30% of the world's cultivated soils and are notorious for causing iron chlorosis in crops (Fageria and Baligar, 2023). This global perspective demonstrates that soil pH is not only a local concern but also a global determinant of agricultural productivity.

Beyond nutrient availability, soil pH profoundly influences biological processes in the soil. Microbial communities, which play critical roles in organic matter decomposition, nitrogen fixation, and nutrient mineralization, are highly sensitive to pH changes. Bacteria generally prefer neutral to slightly alkaline conditions, whereas fungi dominate in more acidic soils (Rousk, Brookes and Bååth, 2010). Key microbial processes such as nitrification, which converts ammonium to nitrate, slow down drastically under acidic conditions, limiting nitrogen availability to plants. Similarly, symbiotic nitrogen fixation by *Rhizobium* in legumes is severely restricted in acidic soils, further reducing the supply of a vital nutrient (Rousk *et al.*, 2010). Thus, soil pH indirectly affects plant nutrition by shaping microbial activity and nutrient cycling.

Plants themselves are not passive in the face of soil pH-induced nutrient imbalances. Over time, they have evolved adaptation strategies to cope with the challenges of acidic and alkaline soils. Acid-tolerant plants, for example, exude organic acids such as malate and citrate to detoxify Aluminium and mobilize phosphorus in acidic soils (Ryan *et al.*, 2011). In alkaline soils, certain grasses release phyto-siderophores that chelate iron, making it more available for uptake. Despite these adaptations, most crops have optimal pH ranges,

typically between 5.5 and 7.5, beyond which yields decline sharply due to nutrient imbalances or toxicities. From a management perspective, regulating soil pH is a central strategy in agriculture to optimize plant nutrition and productivity. Liming is the most common method used to raise soil pH in acidic soils, neutralizing exchangeable aluminium and supplying calcium and magnesium in the process (Raza *et al.*, 2019). Conversely, acidifying amendments such as elemental Sulphur, organic matter and ammonium-based fertilizers are used to lower pH in alkaline soils. These interventions underscore the practical importance of understanding soil pH to sustain soil fertility and crop productivity.

In summary, soil pH plays a central role in plant mineral nutrition by regulating nutrient solubility, microbial activity; hence, shaping plant physiological responses. Both acidic and alkaline soils constitute challenges having potential of limiting agricultural productivity. Consequently, these make the management of soil pH critical for sustainable agriculture. Given its global relevance, the study of soil pH and its relationship with plant mineral nutrition remains a vital area of soil science, with implications for food security, land management and sustainable agricultural development. This review therefore examines in detail the role of soil pH in plant mineral nutrition, focusing on its effects on nutrient availability, microbial processes, plant adaptations, and soil management practices.

SOIL pH AND NUTRIENT AVAILABILITY

Soil pH plays a fundamental role in determining the chemical form, solubility, and ultimately the availability of essential nutrients in soils. Plants require nutrients in ionic forms dissolved in the soil solution, and the concentration of these ions is highly sensitive to pH fluctuations (Marschner, 2012). A soil pH close to neutral (6.0–7.0) generally provides the most favorable conditions for nutrient availability. Deviations from this range, either toward acidity or alkalinity, tend to reduce the availability of one or more nutrients while increasing the solubility of potentially toxic elements. Thus, soil pH functions as a central regulator of nutrient dynamics and plant mineral nutrition.

Macronutrients and soil pH

The availability of macronutrients such as N, P, K, Ca, Mg and Sulphur (S) is strongly affected by soil pH. N, for instance, is absorbed by plants mainly in the nitrate (NO_3) and ammonium (NH_4) forms. Nitrification, the microbial process that converts ammonium to nitrate, is highly sensitive to soil pH, with optimal activity occurring between pH 6.0 and 8.0 (Raza *et al.*, 2019). In strongly acidic soils, nitrifying bacteria are inhibited, reducing nitrate availability and leading to an accumulation of ammonium. Conversely, in alkaline soils, losses of nitrogen through volatilization as ammonia gas increase, thereby lowering nitrogen-use efficiency.

Phosphorus availability is particularly sensitive to pH changes. In acidic soils ($\text{pH} < 5.5$), phosphorus becomes fixed by iron (Fe) and aluminium (Al) oxides, forming insoluble compounds that are unavailable to plants (Havlin *et al.*, 2014). On the other hand, in alkaline soils ($\text{pH} > 7.5$), phosphorus precipitates with Calcium to form calcium Phosphates, which are poorly soluble. Consequently, phosphorus is most available in soils with a pH range of 6.0–7.0. This narrow window highlights the importance of pH

management for crops dependent on high phosphorus availability, such as legumes and cereals.

Potassium availability is less directly affected by pH compared to nitrogen and phosphorus, but acidic conditions can enhance leaching losses of K due to increased mobility of exchangeable cations (Brady and Weil, 2017). Similarly, magnesium and calcium availability declines in strongly acidic soils as they are displaced by hydrogen (H^+) and Aluminium (Al^{3+}) ions on the soil exchange complex. Sulphur, primarily taken up as sulphate (SO_4^{2+}), is less sensitive to pH but may leach rapidly under acidic conditions in high-rainfall areas.

Micronutrients and soil pH

Micronutrients such as Fe, Mn, Zn, Cu, B and Mo are required in small amounts but play critical roles in enzymatic processes, photosynthesis and plant metabolism. Their solubility is highly dependent on soil pH, often in ways opposite to those of macronutrients. Iron and Mn, for example, are more soluble and available in acidic soils but tend to precipitate in neutral to alkaline conditions, leading to deficiencies in crops grown on calcareous soils (Lindsay, 1991). This explains the frequent occurrence of iron chlorosis in crops such as soybean, maize, and citrus grown in alkaline environments. Also, Zn availability is highest in slightly acidic soils and decreases sharply at pH values above 7.0. In contrast, molybdenum availability increases with pH, often reaching toxic levels in strongly alkaline soils but being deficient in acidic conditions (Rousk *et al.*, 2010). Boron availability decreases both under very low and very high pH, indicating a narrower optimal range compared to other micronutrients.

Table 1: Roles of soil pH in plant mineral nutrition

Role of Soil pH	Effect on Plant Mineral Nutrition	Supporting Citation
Nutrient availability	Soil pH regulates solubility of nutrients; acidic soils increase solubility of Fe, Mn, Zn, Cu, but may reduce availability of P, Ca, and Mg.	Marschner, 2012; Havlin <i>et al.</i> , 2014
Phosphorus fixation	At low pH, P is fixed by Fe and Al oxides; at high pH, it is fixed by Ca compounds, reducing its availability.	Hinsinger, 2001; Brady and Weil, 2017
Toxicity of elements	Low pH enhances Al and Mn solubility to toxic levels, impairing root growth and nutrient uptake.	Kochian <i>et al.</i> , 2015
Microbial activity	Soil pH influences microbial populations; acidic soils suppress nitrifying bacteria, reducing N availability, while neutral pH favors optimal microbial processes.	Rousk <i>et al.</i> , 2010
Cation exchange capacity (CEC)	Soil pH affects the proportion of exchangeable bases (Ca^{2+} , Mg^{2+} , K^+) vs. H^+ and Al^{3+} ; higher pH increases base saturation and nutrient retention.	Havlin <i>et al.</i> , 2014

Role of Soil pH	Effect on Plant Mineral Nutrition	Supporting Citation
Chelation and mobility of micronutrients	and pH affects the formation of chelates and the mobility of micronutrients like Fe and Zn; availability decreases in alkaline soils.	Fageria and Baligar, 2008
Soil biological interactions	Symbiotic relationships like N-fixation by legumes are highly sensitive to pH, optimal around neutral ranges.	Zahran, 1999
Overall crop productivity	Soil pH indirectly controls yield through its effect on nutrient balance, toxicity, and biological processes.	Brady and Weil, 2017

Toxic elements and soil pH

Soil pH plays a central role in determining the mobility, bioavailability and eventual toxicity of elements within the soil environment. It acts as a master variable, influencing not only nutrient dynamics but also the behavior of potentially toxic elements such as cadmium (Cd), lead (Pb), arsenic (As), mercury (Hg), and nickel (Ni) (Kabata-Pendias and Mukherjee, 2021). The hydrogen ion concentration of soil governs chemical equilibria such as adsorption, desorption, precipitation and dissolution that dictate how these elements interact with soil colloids, organic matter and mineral surfaces. At low pH (acidic conditions), the solubility of most toxic metals increases, thereby enhancing their availability to plants and soil biota. For instance, cadmium and zinc become more soluble in acidic soils due to protonation of negatively charged sorption sites on clay minerals and organic matter, leading to their release into the soil solution (Sposito, 2022). Similarly, Al^{3+} , which is not toxic in neutral or basic soils, becomes increasingly soluble under acidic conditions, posing significant toxicity risks to plant root systems by inhibiting root elongation and nutrient uptake (Zhao *et al.*, 2023).

Conversely, as soil pH rises toward neutrality or slight alkalinity, most metallic toxicants undergo precipitation or strong adsorption to mineral surfaces such as Fe and Mn oxides, reducing their mobility and biological uptake (Alloway, 2013). However, this generalization does not apply universally. Arsenic, for example, exhibits greater mobility under alkaline and oxidizing conditions, where arsenate (As^{5+}) species dominate. This explains why arsenic toxicity tends to be problematic in calcareous and irrigated soils with high pH (Zhu *et al.*, 2021).

The relationship between soil pH and toxic elements is also intricately linked to organic matter dynamics and redox conditions. In acidic soils, the decomposition of organic matter can release organic acids that further lower pH, amplifying metal mobility. In contrast, under anaerobic or waterlogged conditions, reduction of Fe and Mn oxides can liberate previously immobilized toxic metals, even if the pH remains neutral (Fageria and Baligar, 2023). Thus, pH does not act in isolation but interacts with biological and physicochemical processes to shape the environmental behavior of contaminants. Therefore, maintaining optimal soil pH is essential to minimize metal toxicity and ensure safe food production. Additionally, pH management must be context-specific, integrating

soil type, contaminant identity and cropping system into remediation or fertility strategies.

The soil pH-nutrient balance interaction

Soil pH represents one of the most fundamental variables governing nutrient dynamics in terrestrial ecosystems. It influences the chemical form, solubility and biological availability of both macro- and micronutrients, thereby regulating plant nutrition and overall soil fertility. In essence, soil pH serves as the biochemical thermostat of the soil environment: its shifts, whether toward acidity or alkalinity, profoundly alter the equilibrium between nutrient availability and deficiency (Kabata-Pendias and Mukherjee, 2021). At its core, soil pH determines the charge characteristics of soil colloids and the chemical speciation of nutrients in the soil solution. Under acidic conditions (pH < 6.0), H⁺ and Al³⁺ ions dominate the exchange complex, displacing essential cations such as Ca²⁺, Mg²⁺ and K⁺ from soil colloids (Fageria and Baligar, 2023). This displacement not only reduces the base saturation and nutrient-retention capacity of soils but also increases the leaching losses of these elements. Moreover, acidic conditions enhance the solubility of micronutrients like Fe, Mn, Zn and Cu, sometimes reaching toxic concentrations that impair plant metabolism and root functioning (Kabata-Pendias and Mukherjee, 2021).

In contrast, alkaline soils (pH > 7.5) exhibit a markedly different set of nutrient dynamics. As soil pH rises, the solubility of many micronutrients declines due to the formation of insoluble hydroxides, carbonates, and phosphates. For instance, Fe and Zn deficiencies are widespread in calcareous soils because these metals readily precipitate as Fe(OH)₃ and ZnCO₃ under alkaline conditions, making them unavailable to plants (Rengel, 2015). Similarly, phosphorus (P) availability declines sharply at both low and high pH levels: a phenomenon often described as the “phosphorus availability curve”. In acidic soils, P forms insoluble complexes with Al and Fe oxides, while in alkaline soils, it binds with Ca to form apatite minerals (Hinsinger *et al.*, 2022). This dual sensitivity of phosphorus exemplifies how soil pH mediates the delicate balance between nutrient sufficiency and immobilization. The pH–nutrient relationship also extends to biological processes. Soil microorganisms, which drive organic matter decomposition, nitrogen mineralization and other nutrient-cycling pathways, are highly pH-sensitive. Soil pH indirectly governs nutrient availability through its influence on biological processes and enzymatic functions.

SOIL pH AND MICROBIAL ACTIVITY

Soil pH is one of the most influential environmental variables governing microbial life in soils. It regulates the structure, diversity and functional performance of microbial communities that drive essential biogeochemical processes such as decomposition, nutrient cycling and organic matter stabilization (Rousk *et al.*, 2010; Tripathi *et al.*, 2024). In essence, soil pH acts as an ecological filter that determines which microorganisms can thrive, how efficiently they function and how they interact with plants and the wider soil environment.

At the biochemical level, soil pH influences microbial activity by controlling enzyme functionality and substrate availability. Most soil enzymes, including urease, phosphatase

and dehydrogenase, have optimal activity within a near-neutral pH range (6.0–7.5). Deviations from this range alter enzyme conformation and active site chemistry, leading to reduced catalytic efficiency (Zhou *et al.*, 2023). In strongly acidic soils (pH < 5.0), microbial metabolism tends to slow down, largely because proton toxicity and aluminum solubility disrupt cellular membranes and nutrient uptake (Lauber *et al.*, 2009; Fageria and Baligar, 2023). Conversely, in highly alkaline soils, microbial growth may be constrained by limited carbon availability and the precipitation of essential trace metals such as iron and zinc, which are critical cofactors for enzymatic reactions (Fierer and Jackson, 2024).

The composition of soil microbial communities also shifts markedly along pH gradients. Acidic soils typically favor fungal dominance, as fungi are more tolerant to low pH and can exploit complex organic substrates under such conditions. In contrast, bacterial populations, especially *copio-trophic* groups such as *Proteobacteria* and *Actinobacteria*, tend to flourish in neutral to slightly alkaline soils (Rousk *et al.*, 2010). This shift in community structure has major ecological implications: fungal-dominated systems often exhibit slower decomposition rates and higher carbon stabilization, while bacterial-dominated systems are associated with rapid nutrient mineralization and turnover (Zhao *et al.*, 2023). Thus, soil pH not only affects microbial abundance but also dictates the tempo and trajectory of soil biochemical processes.

Furthermore, microbial feedback mechanisms can modify soil pH over time. For instance, microbial respiration and organic acid exudation can acidify the rhizosphere, whereas microbial-driven denitrification and ammonium uptake can contribute to pH elevation (Slessarev *et al.*, 2022). These feedback loops highlight the bidirectional nature of the soil pH–microbe relationship: pH regulates microbial function and microbial processes, in turn, help shape the pH landscape. Therefore, maintaining an optimal soil pH range is critical for sustaining microbial-driven soil health. Practices such as liming acidic soils or incorporating organic amendments can buffer pH fluctuations and stimulate beneficial microbial activity (Fageria and Baligar, 2023). Likewise, reduced tillage and diversified crop rotations can promote microbial resilience by enhancing pH stability in the rhizosphere.

Soil pH and nitrogen transformations

Soil pH is one of the most critical regulators of N transformations in terrestrial ecosystems. It governs the chemical speciation, microbial mediation, and overall efficiency of N cycling processes, including mineralization, nitrification, denitrification, and ammonium volatilization (Nicol *et al.*, 2022; Fageria and Baligar, 2023). Because nitrogen is an essential yet highly dynamic element in soil systems, understanding how pH controls its transformation pathways is vital for improving nutrient use efficiency, minimizing environmental losses, and sustaining soil fertility.

Nitrogen cycling lies the interplay between soil chemistry and microbial ecology: both profoundly influenced by pH. In acidic soils (pH < 5.5), nitrogen mineralization, which involves the microbial conversion of organic N to NH_4^+ , is generally slowed. Low pH environments inhibit heterotrophic microbial activity, suppress extracellular enzyme production, and reduce substrate accessibility (Zhou *et al.*, 2023). Consequently, organic N accumulates and ammonium release is limited. In contrast, near-neutral pH conditions (6.0–7.5) foster diverse microbial populations and enzyme systems that accelerate the

decomposition of organic residues and facilitate efficient mineralization (Rousk *et al.*, 2010; Fierer and Jackson, 2024).

The effect of soil pH is even more pronounced in nitrification: the aerobic oxidation of ammonium to NO_3^- . This process is mediated primarily by ammonia-oxidizing bacteria and ammonia-oxidizing archaea, both of which exhibit strong pH sensitivity (Prosser *et al.*, 2022). Optimal nitrification rates typically occur between pH 6.5 and 8.0, where NH_3 availability and enzyme stability are maximal. Under acidic conditions, however, proton accumulation inhibits the activity of ammonia monooxygenase, a key enzyme in ammonium oxidation, leading to reduced nitrification efficiency (Fierer and Jackson, 2024). Additionally, nitrifying microorganisms exhibit slower growth rates in low-pH soils, often resulting in the accumulation of ammonium and suppression of nitrate formation.

Denitrification, the reduction of nitrate to gaseous nitrogen forms such as N_2O and N_2 under anaerobic conditions, is also strongly influenced by pH. Denitrifying bacteria perform optimally in near-neutral to slightly alkaline environments, where the activity of reductase enzymes (nitrate, nitrite, and nitrous oxide reductases) is maintained (Fierer and Jackson, 2024). Acidic soils, by contrast, tend to inhibit the final step of denitrification, leading to incomplete reduction and the accumulation of N_2O , a potent greenhouse gas (Rütting *et al.*, 2024). Therefore, low soil pH not only reduces nitrogen availability for plants but also contributes to atmospheric pollution and climate forcing through enhanced N_2O emissions.

Another crucial pH-dependent transformation is ammonia volatilization: the gaseous loss of NH_3 from the soil surface. This process increases sharply in alkaline soils (pH > 7.5), where the equilibrium between NH_4^+ and NH_3 shifts toward the gaseous phase (Sommer *et al.*, 2023). Consequently, nitrogen losses through volatilization are substantial in calcareous or limed soils if fertilizers such as urea are not properly incorporated. Managing soil pH, therefore, plays a dual role: while liming acidic soils enhances mineralization and nitrification, excessive alkalinity can increase volatilization losses and reduce nitrogen-use efficiency.

Soil pH and organic matter decomposition

Soil pH exerts a fundamental control over organic matter (OM) decomposition, serving as a master variable that influences chemical stability, microbial activity, enzyme kinetics and nutrient availability in soil ecosystems. The rate and pathways of organic matter breakdown are not determined solely by the quantity or quality of organic inputs but are intricately regulated by the soil's acidity or alkalinity, which directly shapes microbial communities and the physicochemical environment in which they operate (Fierer and Jackson, 2024). Understanding these interactions is vital for predicting carbon cycling dynamics, greenhouse gas emissions and soil fertility under changing land use and climate regimes.

At the biochemical level, soil pH governs the solubility and ionization of organic molecules, thereby affecting their accessibility to decomposers. In acidic soils (pH < 5.5), humic substances and phenolic compounds often become more recalcitrant due to reduced solubility and increased metal–organic complexation, particularly with Al^{3+} and Fe^{3+} ions (Kleber *et al.*, 2021). These complexes inhibit enzymatic degradation by

blocking reactive sites, slowing the mineralization of carbon and nitrogen. Conversely, under neutral to slightly alkaline conditions (pH 6.0–7.5), organic colloids remain more soluble and readily decomposable, enhancing the release of nutrients through microbial and enzymatic activity (Sinsabaugh *et al.*, 2023).

Microbial activity is profoundly sensitive to pH. Soil pH shapes the structure and function of microbial communities by determining which taxa can thrive and what enzymatic pathways dominate. Fungal populations generally tolerate lower pH levels and often prevail in acidic forest soils, contributing to the slow, oxidative breakdown of lignin and other complex polymers (Rousk *et al.*, 2010; Zhao *et al.*, 2024). In contrast, bacteria dominate under neutral to alkaline conditions, favoring rapid turnover of labile substrates such as cellulose and simple sugars (Tian *et al.*, 2022). This microbial shift across pH gradients alters both the rate and quality of decomposition products, influencing whether soil carbon is stabilized or mineralized to CO₂.

Enzymatic activity, which mediates the transformation of organic substrates into simpler compounds, is also pH-dependent. Extracellular enzymes such as cellulases, proteases, and oxidases exhibit optimal performance within specific pH ranges. Acid phosphatases, for instance, perform efficiently in acidic soils, while alkaline phosphatases dominate in neutral or calcareous environments (German *et al.*, 2011; Zhou *et al.*, 2023). The deviation of soil pH from these enzyme-specific optima can suppress catalytic activity, leading to lower organic matter turnover. Moreover, pH influences the ionization state of enzyme active sites and substrates, thereby modulating enzyme–substrate affinity and overall reaction kinetics. Beyond microbial and enzymatic dynamics, soil pH affects organic matter decomposition indirectly through its influence on soil fauna, nutrient availability and aggregate stability. Earthworms and other decomposer fauna are generally more active in near-neutral soils, where calcium and nitrogen availability support higher biomass and feeding activity (Lavelle *et al.*, 2022). Acidic conditions, on the other hand, can limit faunal abundance and diversity, further retarding organic matter fragmentation and incorporation into mineral soil. Additionally, pH-driven changes in cation exchange capacity and aggregate formation can physically protect organic matter from microbial attack, promoting carbon.

Soil pH and phosphorus-solubilizing microorganisms

Apart from directly affecting nutrient solubility, soil pH indirectly influences nutrient availability through its effects on microorganisms that mediate nutrient transformations. Phosphate-solubilizing bacteria and fungi are known to release organic acids that dissolve otherwise insoluble forms of phosphorus, making it available for plant uptake (Fierer and Jackson, 2024). Their activity is closely tied to soil pH, with fungi being more active in acidic soils while bacteria dominate in neutral soils. Similarly, *arbuscular mycorrhizal* fungi, which enhance phosphorus uptake in many crops, show reduced colonization in extremely acidic or alkaline soils, thereby limiting their effectiveness in promoting nutrient acquisition.

Soil pH and soil-borne pathogens

Soil pH is one of the most decisive environmental factors influencing the occurrence, survival and virulence of soil-borne pathogens. It determines the physicochemical and biological conditions under which pathogenic microorganisms interact with plants and other soil biota. By affecting nutrient availability, microbial competition, enzyme activity

and host defense responses, soil pH indirectly shapes the epidemiology of many soil-borne diseases (Postma *et al.*, 2022; Huber and Watson, 2023). Understanding the pH–pathogen relationship is thus central to sustainable soil and crop health management.

At the ecological level, soil pH governs the diversity and population dynamics of both pathogenic and antagonistic microbes. Most soil-borne pathogens, including *Fusarium oxysporum*, *Rhizoctonia solani*, and *Pythium spp.*, exhibit optimal growth within moderately acidic to neutral pH ranges (5.5–7.0) (Liu *et al.*, 2022). Acidic soils can suppress certain fungal pathogens, while others such as *Plasmodiophora brassicae* (clubroot disease in crucifers) thrive under low-pH conditions (Donald *et al.*, 2019). Conversely, alkaline soils tend to favor bacterial pathogens like *Ralstonia solanacearum*, which causes bacterial wilt in solanaceous crops (Wei *et al.*, 2023). These variable pH optima highlight the species-specific adaptations of pathogens to their soil environment.

One of the primary ways pH affects pathogen activity is through its influence on spore germination and infection structures. For example, *Fusarium chlamydosporum* germinate best near neutral pH, while the resting spores of *P. brassicae* remain dormant at high pH but germinate rapidly under acidic conditions (Donald *et al.*, 2019). Soil pH also modulates the production of pathogenicity-related enzymes such as cellulases, pectinases, and proteases that degrade plant cell walls. These enzymes display strong pH dependency, typically showing maximal activity near neutrality, meaning that deviations from optimal pH can significantly weaken pathogen infectivity (Postma *et al.*, 2022; Huber and Watson, 2023).

Equally important, soil pH controls the structure and activity of microbial communities that antagonize pathogens. Beneficial microbes such as *Trichoderma*, *Bacillus*, and *Pseudomonas* species are sensitive to pH changes, and their abundance often increases under near-neutral to slightly alkaline conditions (Ghorbanpour *et al.*, 2023). These antagonists suppress pathogens through competition, antibiosis, or induced systemic resistance in plants. Hence, in acidic soils, where beneficial microbes are less active, the ecological checks on pathogenic populations are reduced, allowing diseases to proliferate more easily (Rousk *et al.*, 2010; Liu *et al.*, 2022).

Soil chemistry further mediates pathogen dynamics through nutrient availability and metal toxicity. At low pH, micronutrients such as Mn, Fe, and Al become more soluble, sometimes reaching phytotoxic levels that stress plants and weaken their resistance to infection (Huber and Watson, 2023). Additionally, some metals, particularly Mn^{2+} , directly inhibit pathogen growth or enhance host defense enzyme activity (Khan *et al.*, 2022). For example, increasing soil pH through liming often decreases the severity of club-root disease in cabbage because higher pH reduces the availability of Fe and Mn required for *P. brassicae* infection (Donald *et al.*, 2019). However, in alkaline soils, micronutrient deficiencies can suppress plant immunity, predisposing crops to diseases like bacterial wilt and root rot (Wei *et al.*, 2023). At a broader ecological scale, soil pH acts as a regulatory filter shaping pathogen–microbiome–plant interactions. Slight deviations in pH can shift microbial community composition, alter root exudation patterns and change the availability of signaling molecules involved in plant–microbe communication (Zhang *et al.*, 2023). Maintaining an optimal soil pH not only suppresses

pathogen proliferation but also supports a resilient rhizosphere capable of withstanding biotic stress.

Soil pH and its implication in soil fertility and crop production

Soil pH, often described as the master variable of soil chemistry, governs nearly every process that determines soil fertility and plant productivity. It regulates nutrient availability, microbial activity, cation exchange and the solubility of toxic elements thereby exerting both direct and indirect influences on crop growth and yield. Whether in natural or managed agroecosystems, maintaining an optimal soil pH is fundamental to sustaining soil health, nutrient efficiency and resilient crop production systems (Fageria and Baligar, 2023).

At its core, soil pH defines the concentration of hydrogen ions (H^+) in the soil solution, providing a measure of soil acidity or alkalinity. Most crops perform optimally within a slightly acidic to neutral pH range (6.0–7.5), where essential nutrients are readily available, microbial activity is high, and toxic ions are minimal (Havlin *et al.*, 2022). Deviation from this range often disrupts soil nutrient dynamics and biological processes, leading to nutrient imbalances, reduced crop growth, and increased susceptibility to stress (Fierer and Jackson, 2024).

The availability of essential nutrients is profoundly controlled by soil pH. In acidic soils (pH < 5.5), macronutrients such as N, phosphorus P, K, Ca and Mg become less available to plants due to fixation and leaching losses (Zhang *et al.*, 2023). For instance, phosphorus reacts with Al^{3+} and Fe^{3+} to form insoluble compounds that are inaccessible to roots, severely constraining plant growth (Barrow, 2022). Conversely, at high pH (>7.5), P becomes fixed by Ca, while micronutrients such as Fe, Mn, Zn, and Cu precipitate into unavailable forms, resulting in deficiencies in crops like maize, soybean and wheat (Fageria and Baligar, 2023). Both acidic and alkaline extremes impair nutrient balance and crop productivity, highlighting the critical role of pH in nutrient equilibrium.

PLANT ADAPTATION STRAGIES TO SOIL pH

Plants grow in diverse soil environments, many of which are characterized by suboptimal pH conditions that restrict nutrient availability or cause toxicity. While soil management practices such as liming or acidification are often used to modify soil pH, plants themselves have evolved several adaptive mechanisms that enable them to thrive in abnormal soil conditions. These adaptations include morphological, physiological, and biochemical strategies which enhance nutrient uptake, avoiding toxic ions, and modifying the rhizosphere environment. Understanding these adaptation strategies is crucial for crop improvement, particularly in regions where large areas of land are naturally acidic or alkaline and where soil amendments are not economically feasible.

Roots are the primary interface between plants and the soil environment, functioning as dynamic organs that anchor plants, absorb water and nutrients, and sense changes in their surroundings. The capacity of roots to adapt morphologically to diverse soil and climatic conditions is central to plant survival, productivity, and resilience (Lynch, 2022). Root morphological adaptations encompass structural and architectural modifications such as root length, diameter, branching density, root hair proliferation, and symbiotic associations that enable plants to optimize resource acquisition under environmental constraints (de Bauw *et al.*, 2020; Jin *et al.*, 2023).

Root length and architecture

One of the most fundamental root adaptations is the alteration of root system architecture (RSA) in response to soil heterogeneity. In nutrient-poor or dry soils, plants often develop deeper or more extensive root systems to explore larger soil volumes for water and mobile nutrients like nitrate (Hodge *et al.*, 2009). Conversely, in nutrient-rich topsoil layers, roots tend to exhibit a shallower and more branched configuration to maximize uptake efficiency (Zhang *et al.*, 2022). Root elongation and branching are hormonally regulated, primarily through auxin and *cytokinin* signaling, which integrate environmental cues with growth responses (Bishopp *et al.*, 2011). These architectural shifts allow plants to fine-tune resource acquisition strategies across temporal and spatial gradients.

Root diameter and specific root length

Root diameter and specific root length (SRL) defined as root length per unit dry mass are critical indicators of adaptive strategy. Thin roots with high SRL are typically associated with fast-growing species adapted to nutrient-rich or disturbed environments, allowing rapid soil exploration at minimal carbon cost (Miguel *et al.*, 2015). In contrast, thicker roots with low SRL are characteristic of species inhabiting nutrient-poor or compacted soils; these roots are more resistant to mechanical stress and contribute to long-term persistence and mycorrhizal symbiosis (Bergmann *et al.*, 2020). Thus, variation in root thickness represents a functional trade-off between acquisition efficiency and structural longevity.

Root hair proliferation and surface modifications

Root hairs, microscopic extensions of epidermal cells, play a pivotal role in increasing the root surface area for nutrient and water absorption, particularly for immobile nutrients such as phosphorus and zinc (Brown *et al.*, 2013). Under low-phosphorus conditions, plants such as *Arabidopsis thaliana* and maize intensify root hair length and density, thereby enhancing the absorptive interface with the rhizosphere (Miguel *et al.*, 2015). This morphological adaptation is often complemented by exudation of organic acids and phosphatases that mobilize nutrients otherwise inaccessible in the soil matrix (Lyu *et al.*, 2016).

Aerenchyma formation and adventitious roots

In waterlogged or anoxic soils, many plants develop internal air spaces known as aerenchyma, which facilitate oxygen transport from aerial tissues to submerged roots (Colmer and Voesenek, 2009). This adaptation is critical for maintaining aerobic respiration and root viability under flooding. Additionally, adventitious root formation, a common response in rice, maize, and certain wetland plants, enables the regeneration of functional root systems above hypoxic zones (Yamauchi *et al.*, 2018). Such morphological plasticity ensures survival and productivity in oxygen-deficient environments.

Genetic and breeding for pH tolerance

Considerable genetic variation exists among plant species and even among cultivars of the same species in their tolerance to adverse soil pH conditions. For instance, certain rice varieties are more tolerant to acidic soils because of their ability to secrete higher levels of organic acids in response to aluminum stress. Advances in plant breeding and biotechnology are now harnessing these natural variations to develop crop varieties with improved tolerance to suboptimal soil pH. Marker-assisted selection and transgenic

approaches targeting ion transporters, organic acid secretion, and root morphology are promising strategies to enhance crop adaptation to acidic and alkaline soils.

Eco-physiological strategies

Beyond the cellular and genetic mechanisms, plants also adopt eco-physiological strategies to cope with soil pH limitations. Many acid-tolerant species, such as tea (*Camellia sinensis*) and pineapple (*Ananas comosus*), are naturally adapted to low-pH environments through long evolutionary processes. Conversely, alkaline-tolerant species, such as date palm (*Phoenix dactylifera*) and barley (*Hordeum vulgare*), have inherent mechanisms to tolerate low micronutrient solubility and sodium stress. Crop rotation and intercropping systems often exploit these adaptations, where pH-tolerant species improve the soil environment for less tolerant crops, thereby enhancing overall productivity in marginal soils (Raza *et al.*, 2019).

Soil pH and its implication for crop productivity and food security

Understanding plant adaptation strategies to soil pH is crucial for agricultural sustainability. In regions such as sub-Saharan Africa, where acidic soils dominate large areas, breeding for aluminum tolerance and phosphorus efficiency is critical for food security (von Uexküll and Mutert, 1995; Xu *et al.*, 2020). Similarly, in arid and semi-arid zones where alkaline soils prevail, the development of iron-efficient and sodium-excluding crops is essential for maintaining productivity. These strategies reduce reliance on costly soil amendments and chemical fertilizers, thereby making agriculture more resilient and accessible to resource-limited farmers. In summary, plants have developed diverse strategies to cope with the challenges imposed by soil pH. These include morphological changes in root systems, rhizosphere modifications through exudation, ion transport and exclusion mechanisms, symbiotic associations with microbes, genetic variation and eco-physiological adaptations. Harnessing these natural strategies through breeding, biotechnology and ecological management provides a sustainable pathway for improving crop productivity in soils with unfavorable pH conditions.

SOIL pH MANAGEMENT FOR OPTIMAL NUTRIENT UPTAKE

While plants exhibit various adaptation strategies to cope with soil acidity or alkalinity, effective soil management practices remain the most sustainable way of optimizing nutrient availability and ensuring high crop productivity. Soil pH management involves either correcting unfavorable soil conditions or adopting practices that minimize nutrient imbalances caused by extreme pH. Given that soil pH is often referred to as the “master variable” controlling nutrient dynamics, its deliberate management is a cornerstone of soil fertility maintenance and agricultural sustainability (Havlin *et al.*, 2014).

Liming to correct soil acidity

Soil acidity is one of the most pervasive constraints to agricultural productivity, particularly in tropical and subtropical regions where intense weathering and leaching deplete basic cations and accumulate exchangeable Al^{3+} and H^+ (Liu *et al.*, 2017). Acidic soils often exhibit reduced nutrient availability, impaired root growth, and toxicity from aluminum and manganese, all of which hinder plant development and yield potential. Liming, the application of calcium- and magnesium-containing materials, remains the most effective and sustainable corrective measure for soil acidity, restoring favorable chemical and biological conditions for plant growth (Chen *et al.*, 2023).

At the core of liming lies a neutralization reaction in which calcium carbonate (CaCO_3) or other liming materials react with acidic components in the soil. This reaction reduces hydrogen ion concentration, increases soil pH, and displaces exchangeable aluminum ions from the soil colloids. The released Al^{3+} ions precipitate as inert $\text{Al}(\text{OH})_3$, thereby reducing toxicity to plant roots (Chen *et al.*, 2023). As pH rises, the cation exchange complex becomes increasingly saturated with Ca^{2+} and Mg^{2+} , which enhance nutrient uptake and improve soil structure (Sumner and Noble, 2003; Raza *et al.*, 2019). Moreover, liming influences nutrient availability by promoting the release of phosphorus bound to aluminum and iron oxides, thus improving phosphorus use efficiency (Fageria, 2019). It also enhances the microbial mineralization of organic matter, thereby improving nitrogen cycling and overall soil fertility (Zhao *et al.*, 2021).

Use of acidifying amendments for alkaline soils

Soil alkalinity presents a formidable challenge to sustainable crop production, particularly in arid and semi-arid regions where low rainfall, high evapotranspiration, and the accumulation of soluble salts lead to elevated soil pH (generally > 8.0). Such soils are characterized by poor nutrient availability, especially of P, Fe, Mn, Zn and Cu, which are rendered insoluble under alkaline conditions (Qadir *et al.*, 2006; Raza *et al.*, 2019). Additionally, the dominance of sodium carbonate (Na_2CO_3) or bicarbonate (NaHCO_3) compounds in sodic soils adversely affects soil structure and permeability, ultimately impairing root growth and microbial activity (Singh *et al.*, 2020). To restore the chemical balance and enhance fertility in these soils, acidifying agents are employed to lower the pH, displace exchangeable sodium, and improve nutrient bioavailability and soil structure (Fageria, 2019).

The process of soil acidification involves introducing substances that react with soil carbonates, bicarbonates, or basic cations (Na^+ , Ca^{2+} , Mg^{2+}), generating H^+ that lower the pH. This reaction converts insoluble alkaline compounds into soluble salts that can be leached out or utilized by plants (Fageria, 2009). The choice of acidifying agent depends on the type and severity of alkalinity, soil texture, and cropping system. Acidification is especially beneficial in calcareous soils, where excessive calcium carbonate buffers pH and limits nutrient availability (Raza *et al.*, 2019).

ORGANIC MATTER MANAGEMENT

Organic matter and compost

Incorporation of organic materials such as manure, compost, and crop residues contributes to gradual soil acidification through the production of organic acids during decomposition. Carboxylic acids (e.g., citric, malic, oxalic acids) and humic substances released in this process chelate cations like Ca^{2+} and Mg^{2+} , thereby enhancing micronutrient solubility and lowering soil pH over time (Saidy *et al.*, 2012). Moreover, organic amendments improve soil structure, microbial activity, and buffering capacity, which promote a more stable and biologically regulated pH environment (Raza *et al.*, 2019).

Green manuring and leguminous crops

Certain leguminous crops, such as *Sesbania* and *Crotalaria*, when used as green manure, contribute to soil acidification through root respiration and exudation of organic acids during decomposition (Singh *et al.*, 2020). Their deep root systems also help in the leaching of exchangeable sodium and in improving soil aggregation. Integrating

biological acidifiers into cropping systems provides a sustainable and eco-friendly alternative to chemical methods.

Gypsum and calcium amendments

Although gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) does not directly acidify soil, it plays a critical role in reclaiming sodic and alkaline soils by replacing sodium ions on the cation exchange complex with calcium ions. This process reduces soil sodicity and improves permeability and aeration (Qadir *et al.*, 2006; Liu *et al.*, 2017). When used alongside elemental sulfur or organic matter, gypsum enhances the long-term stabilization of soil pH and structure.

Fertilizer management and soil pH

Fertilizer choice and application method significantly influence soil pH over time. Ammonium-based fertilizers (e.g., ammonium sulfate, ammonium nitrate and urea) tend to acidify soils because nitrification releases hydrogen ions. Conversely, nitrate-based fertilizers can lead to alkalization in poorly buffered soils. Thus, fertilizer programs must be designed with consideration of their long-term effects on soil pH (Havlin *et al.*, 2014).

Phosphorus fertilizers, such as superphosphate, can also contribute to localized pH changes in the rhizosphere, affecting nutrient dynamics. In alkaline soils, phosphorus should be applied in bands near roots to minimize fixation with calcium, while in acidic soils, surface applications may reduce fixation with iron and aluminum. Potassium fertilizers generally have minimal impact on soil pH, but excessive use may affect cation balance, especially in low-pH soils.

Crop and variety selection

Selecting crops or crop varieties adapted to prevailing soil pH conditions is an important management strategy, particularly in regions where amending soils is uneconomical. For example, crops such as sorghum, millet and cassava are more tolerant to acidic soils, whereas barley, date palm and cotton can tolerate alkaline soils. Plant breeders have also developed varieties of maize, soybean and wheat with improved tolerance to aluminum toxicity and iron deficiency, making them suitable for cultivation in marginal soils (von Uexküll and Mutert, 1995; Mahler and Tindall, 2017).

Integrated soil pH management

Soil pH is a master variable that governs nearly every facet of soil health and crop productivity: from nutrient solubility and microbial activity to root growth and pollutant mobility. Yet, in many agricultural landscapes, pH imbalances, either acidification or alkalization, remain silent constraints to sustainable food production. Integrated soil pH management offers a holistic approach, combining chemical, organic, and biological strategies to maintain soil pH within an optimal range for plant growth, typically between 5.5 and 7.0 (Havlin *et al.*, 2014; Fageria and Nascente, 2014; Raza *et al.*, 2019). This integrated approach recognizes that soil is a living system and that maintaining its chemical equilibrium requires balancing short-term amendments with long-term ecological processes.

Traditional pH management practices have relied heavily on either liming for acidic soils or the use of acidifying agents for alkaline soils. While effective in the short term, such single-intervention approaches often overlook the complex interactions among soil minerals, organic matter, and microbial processes. Over-liming, for instance, can induce

micronutrient deficiencies, whereas excessive application of sulfur-based acidifiers can create localized toxicity (Bolan *et al.*, 2003; Zhao *et al.*, 2021). Integrated soil pH management, therefore, seeks to harmonize chemical amendments with organic matter management and biological processes. It is guided by the principle that the soil's buffering capacity and biological resilience must be enhanced, not merely chemically corrected (Lal, 2020).

Implications for sustainable agriculture

Effective soil pH management enhances nutrient availability, reduces the risk of toxicity, improves soil biological activity, and ultimately supports higher and more sustainable crop yields. In the context of global agriculture, managing soil acidity is particularly critical in the humid tropics, which account for a large proportion of acidic soils worldwide, while alkaline soil management is essential in arid and semi-arid regions where calcareous soils dominate (von Uexküll and Mutert, 1995; Mahler and Tindall, 2017). By integrating soil amendments with crop and fertilizer management, farmers can maintain favorable pH conditions, reduce input costs and improve nutrient-use efficiency, thereby contributing to food security and environmental sustainability.

In summary, soil pH management for optimal nutrient uptake involves a combination of practices including liming for acidic soils, acidifying amendments for alkaline soils, organic matter management, careful fertilizer uses and crop selection. Integrated management strategies that consider both short-term corrective measures and long-term sustainability are essential for ensuring that soil pH remains within a range favorable for crop growth and nutrient availability.

SOIL pH MANAGEMENT STRATEGIES FOR OPTIMIZING PLANT MINERAL NUTRITION

Given the central role of soil pH in determining nutrient solubility, mobility, and plant uptake, managing soil pH effectively is one of the most important agronomic practices for ensuring sustained soil fertility and agricultural productivity. Farmers, soil scientists, and land managers employ several strategies to either raise or lower soil pH depending on the prevailing soil conditions and crop requirements. In this section, key management approaches are highlighted.

Liming to correct soil acidity

The most common method of raising soil pH is the application of lime, CaCO_3 or other liming materials such as dolomite, quicklime, or hydrated lime. Liming neutralizes H^+ and Al^{3+} in acidic soils, thereby increasing pH and reducing metal toxicities (Fageria and Nascence, 2014). In addition to correcting soil acidity, lime also supplies essential nutrients such as Ca^{2+} and magnesium Mg^{2+} , which further enhance soil fertility. Proper liming improves P availability, reduces Mn toxicity, and creates a more favorable environment for soil microbial activity. For long-term effectiveness, lime application should be based on soil test results and uniformly incorporated into the soil profile (Havlin *et al.*, 2014; Mahler and Tindall, 2017).

Acidifying agents for alkaline soils

In areas where soils are highly alkaline, particularly calcareous soils with pH values greater than 7.5, lowering the pH is often required to enhance micronutrient availability. Common acidifying agents include elemental sulfur, ammonium sulfate and iron sulfate,

which generate acidity as they undergo microbial or chemical transformations in the soil (Mahler and Tindall, 2017). For example, the oxidation of elemental sulfur by *Thiobacillus* bacteria produces sulfuric acid, which effectively lowers soil pH. Additionally, the application of organic matter such as compost and green manure helps to buffer soil alkalinity by releasing organic acids during decomposition (Rengel, 2015).

Organic matter management

Balanced fertilization is a cornerstone of sustainable soil management because it harmonizes nutrient supply while maintaining soil chemical equilibrium, especially soil pH. The practice involves applying essential nutrients: macronutrients like nitrogen (N), phosphorus (P), and potassium (K), as well as micronutrients in the right proportions and often in combination with organic inputs such as manure or compost. This integrated approach minimizes the risk of soil acidification, which commonly arises from prolonged and unbalanced use of ammonium-based fertilizers (Li *et al.*, 2021).

The influence of fertilization on soil pH is primarily governed by the chemical form of nitrogen, the balance among nutrients and the buffering capacity caused by organic matter (Guo *et al.*, 2010; Xu *et al.*, 2020). Ammonium fertilizers tend to release hydrogen ions during nitrification, leading to acidification, whereas nitrate-based sources may slightly raise or stabilize pH (Yang *et al.*, 2023). When mineral fertilizers are applied alone, they often reduce soil pH over time; however, when integrated with organic matter or crop residues, they enhance the soil's cation exchange capacity and supply base cations (Ca^{2+} , Mg^{2+}), mitigating acidification (Chen *et al.*, 2023).

Empirical evidence from long-term field experiments consistently supports this pattern. In red soils of China, for instance, exclusive nitrogen fertilization lowered pH by about 1.5 units over 18 years, while balanced fertilization with manure maintained or increased pH (Liu *et al.*, 2017). Similar trends were reported in tropical and subtropical soils, where integrating organic materials with NPK fertilizers sustains pH stability and enhances microbial activity and nutrient cycling (Guo *et al.*, 2010; Liu *et al.*, 2017). Balanced nutrient supply not only regulates acid–base balance but also promotes microbial and root-mediated buffering, ensuring greater resilience against acidification (Guo *et al.*, 2010).

In essence, balanced fertilization fosters a dynamic equilibrium in soil systems by reducing excessive hydrogen ion accumulation, improving soil buffering capacity and maintaining a favorable environment for nutrient availability and biological activity. This strategy sustains soil fertility, enhances crop productivity and protects soil against long-term degradation (Xu *et al.*, 2020). Hence, incorporating both organic and inorganic sources in a balanced nutrient regime remains an indispensable tool for maintaining optimal soil pH and ensuring the longevity of productive agricultural ecosystems.

Balanced fertilization

Organic matter management plays a pivotal role in controlling soil pH and maintaining chemical stability within the soil ecosystem. The addition of organic inputs such as manure, compost, crop residues, or green manures influences soil acidity through a combination of chemical, biological and buffering mechanisms (Guo *et al.*, 2019; Chen *et al.*, 2023). When organic materials decompose, they release base cations: Ca^{2+} , Mg^{2+} and K^{+} that replace H^{+} and Al^{3+} on exchange sites, effectively neutralizing acidity and raising

soil pH (Guo *et al.*, 2019). However, this process is not entirely linear. During the early stages of decomposition, microbial oxidation of organic compounds can release weak organic acids such as citric and oxalic acids, which may temporarily lower soil pH until they are mineralized or buffered by the soil matrix (Guo *et al.*, 2019). Over time, these transient effects diminish as decomposition stabilizes and buffering capacity strengthens through the accumulation of humified organic matter (Liu *et al.*, 2022).

Organic matter also enhances soil CEC, providing more sites for charge balance and thereby improving the soil's resistance to pH fluctuations (Zhang *et al.*, 2022). Soils enriched with organic carbon show greater resilience against acidification because of their ability to absorb excess hydrogen ions and release base ions when needed (Wang *et al.*, 2021). Moreover, under fluctuating redox or wet–dry cycles, organic substrates can stimulate microbial processes such as sulfate or iron reduction, which consume protons and contribute to gradual pH increases (Liu *et al.*, 2022). Long-term field studies consistently affirm that integrating organic amendments with or without mineral fertilizers helps restore or maintain optimal pH. For instance, continuous compost or manure application in acidic soils increased pH by 0.5–1.5 units over several years compared to unfertilized controls. Likewise, organic inputs not only correct soil acidity but also enhance microbial activity, nutrient availability and overall soil buffering capacity, creating a more chemically and biologically stable environment (Li *et al.*, 2020; Chen *et al.*, 2023). Therefore, effective organic matter management moderates soil acidity through cation replenishment, enhanced buffering capacity and biological stabilization. These processes make it indispensable for sustaining soil fertility, improving nutrient efficiency and supporting long-term agroecosystem productivity, especially in regions facing chronic soil acidification (Liu *et al.*, 2022).

Use of pH-resilient crop varieties

Soil pH exerts a profound influence on plant growth by regulating nutrient availability, microbial dynamics, and the solubility of potentially toxic elements. In both acidic and alkaline environments, extreme pH levels often lead to nutrient imbalances and physiological stress that constrain crop productivity. The development and use of pH-resilient crop varieties therefore represent a pivotal adaptation strategy for ensuring agricultural sustainability under diverse and changing soil conditions (Fageria and Baligar, 2023; Zhang *et al.*, 2024). pH-resilient crops are those capable of maintaining normal physiological and biochemical functions across a wide pH spectrum. These varieties exhibit enhanced tolerance to either high concentrations of hydrogen ions in acidic soils or bicarbonate and carbonate ions in alkaline conditions. Their adaptability is often achieved through complex genetic and physiological traits that modulate root ion transport, organic acid exudation, and rhizosphere pH regulation (Chen *et al.*, 2023). For instance, certain rice and maize genotypes tolerant to soil acidity exude organic acids such as citrate and malate, which chelate toxic Al^{3+} and prevent their entry into root cells (Huang *et al.*, 2023). Similarly, in alkaline soils, wheat and barley varieties with efficient iron uptake systems can overcome iron chlorosis by releasing phytosiderophores that solubilize Fe^{3+} , maintaining chlorophyll synthesis and photosynthetic competence (Wang *et al.*, 2022).

The use of pH-resilient varieties also supports improved nutrient use efficiency. In acidic environments, for example, tolerant cultivars often maintain superior uptake of

phosphorus, calcium, and magnesium by sustaining root membrane integrity and selective ion permeability (Rao *et al.*, 2021). Conversely, in alkaline or sodic soils, tolerant genotypes reduce Na accumulation through selective ion exclusion mechanisms and enhanced potassium retention, thereby maintaining cytoplasmic ion homeostasis and osmotic balance (Shabala *et al.*, 2020). These physiological attributes not only enhance plant performance but also reduce the need for frequent soil amendments, aligning with principles of resource-efficient and climate-smart agriculture.

Genomic and molecular breeding approaches have accelerated the identification of key genes and quantitative trait loci (QTLs) responsible for pH tolerance. For instance, the ALMT1 and MATE genes are well-characterized for aluminum tolerance in acidic soils, while YS1 and IRT1 transporters are known to enhance iron acquisition in high-pH environments (Foy *et al.*, 2022; Zhang *et al.*, 2024). Advances in CRISPR/Cas genome editing and transcriptomic profiling are now enabling the precise manipulation of such genes to produce cultivars with enhanced resilience to pH stress, without compromising yield potential or nutritional quality (Xu *et al.*, 2023).

Soil test and monitoring

Soil pH is a central determinant of soil fertility and ecosystem health, influencing nutrient solubility, microbial activity, and plant productivity. Its control is not a one-time corrective act but a dynamic management process guided by continuous testing and monitoring. Without reliable and timely information on soil acidity or alkalinity, corrective interventions such as liming, organic amendment, or acidification can become inefficient or even counterproductive. Thus, soil testing and monitoring serve as the diagnostic foundation of soil pH management, providing the data needed to maintain optimal chemical balance, improve crop performance, and safeguard long-term soil sustainability (Havlin *et al.*, 2014; Fageria and Nascente, 2014).

Soil pH testing is the cornerstone of evidence-based soil management. It enables farmers, agronomists, and researchers to assess the chemical environment in which roots operate and determine whether nutrient deficiencies or toxicities are pH-related (Brady and Weil, 2017). Because soil pH directly affects the availability of macronutrients such as N, P and K, as well as micronutrients like Fe, Zn and Mn, regular testing allows for precise correction strategies (Bolan *et al.*, 2003; Zhao *et al.*, 2021). For instance, when pH falls below 5.5, Al^{3+} and Mn^{2+} solubility increases, which can impair root growth and inhibit nutrient uptake. Conversely, at pH values above 7.5, essential micronutrients like Fe, Zn and Cu become insoluble, leading to hidden hunger and yield loss (Raza *et al.*, 2019). Accurate pH testing helps identify these risks early, ensuring that management interventions whether liming or acidification: are both effective and economically justified.

Integrated soil pH management

No single strategy is universally effective; hence, integrated soil fertility and pH management is essential. This involves a combination of liming, organic matter addition, balanced fertilization, crop rotation, and the use of tolerant crop varieties. Such an integrated approach not only corrects soil pH but also improves nutrient use efficiency, soil structure, microbial activity, and overall crop productivity (Rengel, 2015). Effective soil pH management is indispensable for optimizing plant mineral nutrition. By adopting context-specific strategies whether liming in acidic soils or applying acidifying agents in

alkaline soils farmers can enhance nutrient availability, minimize toxicities, and sustain agricultural productivity. These practices are particularly critical in regions with fragile soils that are prone to nutrient depletion and pH imbalances due to continuous cultivation and inappropriate fertilizer use.

CONCLUSION

Soil pH plays a pivotal role in regulating the availability, mobility, and uptake of mineral nutrients by plants. It directly influences the solubility of essential macronutrients such as phosphorus, nitrogen, and potassium, as well as micronutrients like iron, zinc, manganese, and copper. When soil pH deviates from the optimum range (generally 5.5–7.0 for most crops), nutrient deficiencies or toxicities emerge, limiting plant growth and productivity. Acidic soils are commonly associated with aluminum and manganese toxicities and reduced phosphorus availability, while alkaline soils often restrict the solubility of micronutrients such as Fe, Zn, and Mn. Effective management of soil pH through liming, application of acidifying agents, incorporation of organic matter, balanced fertilizer use, and adoption of pH-tolerant crop varieties is essential for maintaining nutrient balance and improving soil fertility. Regular soil testing and site-specific management remain indispensable for guiding these interventions. Ultimately, understanding and managing soil pH is central to sustainable agriculture. By ensuring that soils remain within the optimal pH range, farmers can maximize nutrient use efficiency, enhance crop yields and safeguard long-term soil productivity.

CONFLICT OF INTEREST: The authors report no conflicts of interest

REFERENCE

- Alloway, B. J. (2011). *Heavy Metals in Soils: Trace Metals and Metalloids in Soils and their Bioavailability* (3rd ed.). Springer.
- Abrol, I. P., Yadav, J. S. P., and Massoud, F. I. (1988). *Salt-Affected Soils and Their Management*. FAO Soils Bulletin No. 39, FAO, Rome.
- Bolan, N. S., Adriano, D. C., and Curtin, D. (2003). Soil acidification and liming interactions with nutrient and heavy metal transformation and bioavailability. *Advances in Agronomy*, 78, 215–272.
- Brady, N.C., and Weil, R.R. (2017). *The Nature and Properties of Soils* (15th ed.). Pearson.
- Barrow, N. J. (2022). The Effects of Soil pH on Phosphorus Availability: Revisiting a Century of Research. *Advances in Agronomy*, 179, 85–129.
- Bergmann, J., Ryo, M., Prati, D., Hempel, S., and Rillig, M. C. (2020). Root traits are more than analogues of leaf traits: The role of root diameter in plant strategies. *Functional Ecology*, 34(4), 802–815.
- Bishopp, A., Help, H., and Helariutta, Y. (2011). Hormone interactions in the regulation of plant development. *Annual Review of Cell and Developmental Biology*, 27, 265–289.
- Brown, L. K., George, T. S., Dupuy, L. X., and White, P. J. (2013). A conceptual model of root hair ideotypes for future agricultural environments. *Annals of Botany*, 112(2), 317–330.

- Chen, J., Liu, Q., and Yang, C. (2023). Root physiological mechanisms of crop tolerance to soil acidity and alkalinity. *Plant and Soil*, 489(1–2), 45–63.
- Colmer, T. D., and Voesenek, L. A. C. J. (2009). Flooding tolerance: Suites of plant traits in variable environments. *Functional Plant Biology*, 36(8), 665–681.
- de Bauw, P., van Asten, P., Jassogne, L., and Merckx, R. (2020). Root plasticity under contrasting moisture regimes in banana. *Plant and Soil*, 455(1–2), 167–183.
- Donald, E. C., Porter, I. J., and Lancaster, R. A. (2019). Influence of Soil pH on the Survival and Infection of Plasmodiophora brassicae in Canola and Cabbage. *Plant Pathology*, 68(8), 1423–1433.
- Fageria, N. K. (2009). *The use of nutrients in crop plants*. CRC Press.
- Fageria, N. K., and Baligar, V. C. (2023). Soil pH Influence on Nutrient Dynamics and Crop Productivity. *Advances in Agronomy*, 185, 1–48.
- Fageria, N. K., and Nascente, A. S. (2014). Management of soil acidity of South American soils for sustainable crop production. *Advances in Agronomy*, 128, 221–275.
- Fageria, N.K., and Baligar, V.C. (2008). *Ameliorating soil acidity of tropical Oxisols by liming for sustainable crop production*. *Advances in Agronomy*, 99, 345–399.
- Fageria, N. K., and Baligar, V. C. (2023). Soil Chemical Properties and Plant Growth: A Modern Review. *Advances in Agronomy*, 185, 1–48.
- Foy, C. D., Huang, C. F., and Kochian, L. V. (2022). Genetic mechanisms of aluminum and iron tolerance in cereal crops. *Frontiers in Plant Science*, 13, 945623.
- Fierer, N., and Jackson, R. B. (2024). The Diversity and Biogeography of Soil Microbial Communities: Revisiting the pH Paradigm. *Nature Reviews Microbiology*, 22(1), 12–27.
- Guo, J. H., Liu, X. J., Zhang, Y., Shen, J. L., Han, W. X., Zhang, W. F., ... and Zhang, F. S. (2010). Significant acidification in major Chinese croplands. *Science*, 327(5968), 1008–1010.
- German, D. P., Weintraub, M. N., Grandy, A. S., et al. (2011). Optimization of Enzyme Assay Techniques for Measuring Soil Extracellular Enzyme Activity under Variable pH. *Soil Biology and Biochemistry*, 43(7), 1387–1397.
- Ghorbanpour, M., Omidvari, M., and Khan, M. R. (2023). Soil pH-Mediated Regulation of Plant Beneficial Microbes: Implications for Biocontrol of Soil-Borne Diseases. *Frontiers in Microbiology*, 14, 1178349.
- Huber, D. M., and Watson, R. D. (2023). The Role of Soil pH in Plant–Pathogen Interactions: Mechanisms and Management. *Annual Review of Phytopathology*, 61, 195–220.
- Havlin, J. L., Tisdale, S. L., Nelson, W. L., and Beaton, J. D. (2022). *Soil Fertility and Fertilizers: An Introduction to Nutrient Management* (9th ed.). Pearson.

- Hinsinger, P. (2001). Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes. *Plant and Soil*, 237(2), 173–195.
- Hodge, A., Berta, G., Doussan, C., Merchan, F., and Crespi, M. (2009). Plant root growth, architecture and function. *Plant and Soil*, 321(1–2), 153–187.
- Haynes, R. J., and Naidu, R. (1998). Influence of lime, fertilizer, and manure applications on soil organic matter content and soil physical conditions: A review. *Nutrient Cycling in Agroecosystems*, 51(2), 123–137.
- Jin, K., White, P. J., Whalley, W. R., Shen, J., and Shi, L. (2023). Root phenotypic plasticity for nutrient acquisition: Implications for crop improvement. *Trends in Plant Science*, 28(1), 52–64.
- Kochian, L. V., Piñeros, M. A., Liu, J., and Magalhaes, J. V. (2015). Plant adaptation to acid soils: The molecular basis for crop aluminum resistance. *Annual Review of Plant Biology*, 66(1), 571–598.
- Khan, M. R., Iqbal, A., and Ali, A. (2022). Metal Ions, Soil pH, and Pathogen Suppression: Linking Soil Chemistry to Disease Resistance. *Soil Systems*, 6(3), 55.
- Kabata-Pendias, A., and Mukherjee, A. B. (2021). Trace Elements from Soil to Human. CRC Press.
- Kleber, M., Sollins, P., and Sutton, R. (2021). A Conceptual Model of Organic Matter Stabilization: The Role of Soil pH and Mineral Interactions. *Soil Systems*, 5(1), 12.
- Lavelle, P., Decaëns, T., and Blouin, M. (2022). Soil Fauna-Mediated Decomposition Processes under Varying pH Conditions. *Applied Soil Ecology*, 181, 104657.
- Liu, Y., Zhang, S., and Li, W. (2022). The Influence of Soil pH on Fungal Pathogen Communities and Disease Incidence in Agricultural Soils. *Soil Biology and Biochemistry*. 165, 108552.
- Lauber, C. L., Strickland, M. S., Bradford, M. A., and Fierer, N. (2009). The Influence of Soil pH on Microbial Community Structure in Soils. *Soil Biology and Biochemistry*, 41(5), 977–985.
- Lal, R. (2020). Soil organic matter and sustainable agriculture. *Journal of Soil and Water Conservation*, 75(2), 123A–132A.
- Lyu, Y., Tang, H., Li, H., Zhang, F., and Rengel, Z. (2016). Phosphorus acquisition and utilization in maize: Root morphology, exudation, and microbial associations. *Journal of Experimental Botany*, 67(12), 3617–3629.
- Lynch, J. P. (2022). Root phenotypes for improved nutrient capture: An emerging opportunity for plant breeding. *Annual Review of Plant Biology*, 73, 361–388.
- Lindsay, W. L. (1995). Chemical Equilibria in Soils. Wiley-Blackwell.
- Miguel, M. A., Postma, J. A., and Lynch, J. P. (2015). Phosphorus efficiency in maize: Root hair length and density enhance phosphorus uptake from low-phosphorus soil. *Plant Physiology*, 166(2), 747–758.

- Mahler, R. L., and Tindall, T. A. (2017). Soil acidification: Causes, effects, and management practices. *Soil Science Society of America Journal*, 81(2), 352–365.
- Marschner, P. (2012). *Marschner's Mineral Nutrition of Higher Plants* (3rd ed.). Academic Press.
- Nicol, G. W., Prosser, J. I., and Leininger, S. (2022). Environmental Control of Ammonia-Oxidizing Microorganisms Across pH Gradients. *Frontiers in Microbiology*, 13, 849324.
- Prosser, J. I., He, Y., and Gubry-Rangin, C. (2022). Soil pH as a Determinant of Nitrification Rates and Ammonia Oxidizer Community Structure. *ISME Journal*, 16(5), 1155–1168.
- Postma, J., van Os, G. J., and Bonanomi, G. (2022). Soil pH and Microbial Antagonism in Disease Suppressive Soils: A Review. *Soil Ecology Letters*, 4(4), 259–275.
- Qadir, M., Oster, J. D., Schubert, S., Noble, A. D., and Sahrawat, K. L. (2006). Phytoremediation of sodic and saline-sodic soils. *Advances in Agronomy*, 96, 197–247.
- Rao, I. M., Beebe, S. E., and Blair, M. W. (2021). Root adaptations to soil acidity and nutrient deficiency in legumes. *Field Crops Research*, 266, 108133.
- Raza, M. A. S., Saleem, M. F., and Shah, G. M. (2019). Managing alkaline soils for crop production: A review. *Soil Use and Management*, 35(4), 563–577.
- Rengel, Z. (2015). Availability of Mn, Zn and Fe in the rhizosphere. *Journal of Soil Science and Plant Nutrition*, 15(2), 397–409.
- Rütting, T., Hénault, C., and Clough, T. (2024). Soil pH as a Regulator of Nitrous Oxide Emissions: Mechanistic Insights and Mitigation Strategies. *Global Change Biology*, 30(2), e16232.
- Rousk, J., Brookes, P.C., and Bååth, E. (2010). The microbial PLFA composition as affected by pH in an arable soil. *Soil Biology and Biochemistry*, 42(3), 516–520.
- Sposito, G. (2022). *The Chemistry of Soils* (3rd ed.). Oxford University Press.
- Sommer, S. G., Webb, J., and Chadwick, D. R. (2023). Ammonia Volatilization and Soil pH: Mechanisms, Measurements, and Mitigation. *Agricultural Systems*, 214, 103693.
- Sinsabaugh, R. L., Turner, B. L., and Talbot, J. M. (2023). Soil Enzyme Responses to Changing pH and Organic Matter Inputs: A Global Perspective. *Frontiers in Environmental Science*, 11, 1190043.
- Slessarev, E. W., Lin, Y., and Wieder, W. R. (2022). Microbial Feedbacks to Soil pH Alter Biogeochemical Cycling. *Global Change Biology*, 28(17), 5231–5244.
- Sumner, M. E., and Noble, A. D. (2003). Soil acidification: The world story. In Rengel, Z. (Ed.), *Handbook of Soil Acidity* (pp. 1–28). Marcel Dekker.

- Saidy, A. R., Smernik, R. J., and Baldock, J. A. (2012). Organic matter decomposition and soil acidification: The role of carboxylic acids. *Soil Biology and Biochemistry*, 47, 125–132.
- Singh, A., Bhattacharya, R., and Sharma, P. (2020). Management of sodic and alkaline soils for sustainable agriculture. *Journal of Soil Science and Plant Nutrition*, 20(4), 1680–1696.
- Shabala, S., Chen, G., and Bose, J. (2020). Adaptation of plants to alkaline soils: Physiological and molecular perspectives. *Annual Plant Reviews Online*, 3(2), 89–115.
- Tripathi, B. M., Jung, J. Y., and Kim, M. (2024). Soil pH as a Determinant of Microbial Metabolic Potential and Carbon Cycling Efficiency. *Environmental Microbiology Reports*, 16(2), 140–153.
- Tian, Q., Wang, M., and Chen, H. (2022). Microbial Community Shifts and Functional Adaptation along Soil pH Gradients: Implications for Organic Matter Decomposition. *Applied and Environmental Microbiology*, 88(19), e00523–22.
- Tilman, D., Balzer, C., Hill, J., and Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*, 108(50), 20260–20264.
- Von Uexküll, H. R., and Mutert, E. (1995). Global extent, development and economic impact of acid soils. *Plant and Soil*, 171(1), 1–15.
- Wei, C., Wu, X., and Jiang, G. (2023). Soil pH Effects on *Ralstonia solanacearum* Survival and Tomato Bacterial Wilt Suppression. *Phytopathology*, 113(4), 745–758.
- Wang, X., Li, H., and Zhao, F. J. (2022). Molecular mechanisms of iron deficiency tolerance in crops under alkaline conditions. *Plant Physiology and Biochemistry*, 187, 62–73.
- Xu, Y., He, G., and Wang, J. (2023). Genome editing and multi-omics approaches for improving soil pH tolerance in crops. *Plant Biotechnology Journal*, 21(1), 44–59.
- Yamauchi, T., Pedersen, O., and Nakazono, M. (2018). Adaptation of plants to flooding stress: Morphological and anatomical changes and oxygen-dependent regulation of gene expression. *Plant Cell and Environment*, 41(2), 300–314.
- Zhao, X., Zhang, Y., and Li, W. (2023). Aluminum Toxicity and Soil Acidity: Mechanisms and Agricultural Implications. *Soil Systems*, 7(2), 45.
- Zhu, Y.-G., Chen, S. B., and He, Y. Q. (2021). Arsenic in Soil–Plant Systems: Biogeochemical Behavior and Risk Assessment. *Environmental Science and Technology*, 55(18), 12188–12205.
- Zhou, J., Deng, Y., and Guo, X. (2023). Soil Enzyme Sensitivity to pH and Temperature: A Meta-Analysis of Global Data. *Global Ecology and Biogeography*, 32(4), 742–756.

Zhao, J., Zhang, R., Xue, C., Xun, W., Sun, L., Xu, Y., and Shen, Q. (2021). Liming enhances microbial-mediated nutrient transformation and plant growth in acid soils. *Applied Soil Ecology*, 157, 103745.

Zhang, L., Zhao, X., and Ma, Q. (2024). Genetic improvement for pH resilience in crop plants: Challenges and prospects. *Frontiers in Agronomy*, 6, 1221459.