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Soil pH as a Master Variable: Implications for Soil Fertility and Crop Productivity – A Review

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Abstract

Soil pH is widely recognized as a “master variable” that regulates a broad range of chemical, biological, and physical processes in soils, thereby exerting a strong influence on soil fertility and crop productivity. This review synthesizes current knowledge on the role of soil pH in controlling nutrient availability, microbial activity, root growth, and overall plant performance, with particular emphasis on its implications for sustainable agricultural management. Evidence from field and laboratory studies demonstrates that soil pH governs the solubility and chemical forms of essential macro- and micronutrients, influences the activity and composition of soil microbial communities, and affects soil buffering capacity and biogeochemical cycling. Acidic soils are often constrained by aluminium and manganese toxicity and reduced availability of base cations, whereas alkaline soils commonly suffer from micronutrient deficiencies and phosphorus fixation. In contrast, neutral to slightly acidic soils generally provide optimal conditions for nutrient uptake, microbial functioning, and root development, resulting in improved crop growth and yield. The review further discusses factors controlling soil pH, including parent material, climate, biological processes, and management practices, and evaluates key strategies for pH management such as liming, organic amendments, acidifying inputs, and precision soil testing. Finally, emerging research directions, including site-specific pH management and integration with climate-smart agriculture, are highlighted. Overall, maintaining soil pH within an optimal range is fundamental for enhancing nutrient use efficiency, sustaining soil health, and achieving long-term agricultural productivity.

Keywords: Soil pH, Soil Fertility, Crop Productivity, Nutrient Availability, Soil Chemistry, Microbial Activity, Soil Health, pH Management, Agricultural Sustainability, Soil–Plant Interaction

1. Introduction

Soil pH is a critical factor influencing soil health, plant growth, and overall agricultural productivity. It refers to the degree of acidity or alkalinity of the soil and is widely regarded as a **“master variable”** because it regulates numerous physical, chemical, and biological processes in the soil system. Soil pH is measured on a logarithmic scale ranging from 0 to 14, where values below 7 indicate acidic soils, values above 7 indicate alkaline soils, and values around 7 represent neutral conditions. This single parameter exerts a strong control over nutrient availability, microbial activity, enzymatic reactions, and plant root development, thereby directly affecting soil fertility and crop performance [1,4]. The pH of soil strongly influences the solubility and mobility of essential plant nutrients, which in turn determines their uptake by crops. In addition, soil pH plays a vital role in shaping the composition and activity of soil microbial communities, which are responsible for organic matter decomposition, nutrient mineralization, and biogeochemical cycling [1,2]. Therefore, soil pH serves as a central regulator of soil ecosystem functioning and agricultural sustainability. In agricultural practice, understanding and managing soil pH is fundamental for ensuring healthy plant growth and optimizing crop yields. Most agricultural crops perform best in neutral to slightly acidic soils (pH 6.0–7.0); however, several crops have specific pH requirements. For instance, crops such as blueberry prefer strongly acidic soils, whereas asparagus and some legumes grow better under slightly alkaline conditions [3,4]. This crop-specific response to soil pH highlights the importance of proper pH management in achieving maximum productivity and maintaining soil health.

Soil pH also has a profound effect on nutrient availability and potential toxicity. In acidic soils, elements such as iron (Fe), manganese (Mn), and aluminum (Al) become more soluble, which may lead to toxicity and restricted root growth. Conversely, in alkaline soils, the availability of nutrients such as iron, zinc (Zn), and phosphorus (P) is reduced due to precipitation and fixation reactions, often resulting in nutrient deficiency symptoms in crops [2,5]. Hence, maintaining soil pH within an optimum range is essential to avoid nutrient imbalances, enhance nutrient use efficiency, and improve crop productivity. In this context, soil pH truly functions as a master variable governing soil fertility and agricultural performance.

2. Fundamentals of Soil pH

Soil pH is a measure of the hydrogen ion (H^+) concentration in the soil solution and serves as an indicator of soil acidity or alkalinity. It plays a fundamental role in determining soil chemical reactions, nutrient transformations, microbial activity, and the overall health of the soil ecosystem. Because many soil processes are pH-dependent, even small changes in soil pH can lead to significant alterations in nutrient availability and biological activity [1,2]. Soil pH is commonly measured using a pH meter in a soil–water or soil–salt (e.g., $CaCl_2$) suspension. The measured value reflects the intensity of soil acidity or alkalinity and provides a practical basis for making soil management decisions, such as liming acidic soils or applying acidifying amendments to alkaline soils. The natural pH of soils is influenced by several factors, including parent material, climate, vegetation, topography, and land-use practices. In humid regions, soils tend to become more acidic due to leaching of basic cations, whereas in arid and semi-arid regions, soils often become alkaline because of the accumulation of calcium, magnesium, and sodium salts [3,5]. Various soil processes contribute to pH variation over time, including organic matter decomposition, nitrification, root exudation, fertilizer application, and irrigation water quality. For example, the use of ammonium-based fertilizers promotes soil acidification through nitrification, while the application of lime increases soil pH by neutralizing hydrogen and aluminum ions in the soil exchange complex [1,4]. These dynamic processes demonstrate that soil pH is not a static property but a manageable factor that can be manipulated to improve soil fertility and crop productivity. Thus, understanding the fundamentals of soil pH is essential for sustainable soil management, as it provides the scientific basis for correcting soil constraints, improving nutrient availability, and enhancing crop performance. Given its central role in controlling soil chemical and biological processes, soil pH justifiably deserves recognition as a master variable in soil fertility and agricultural production systems.

3. Definition of Soil pH

Soil pH refers to the concentration of hydrogen ions (H^+) in the soil solution and is a fundamental indicator of soil acidity or alkalinity. It is commonly measured on a logarithmic scale ranging from 0 to 14, where:

- **pH < 7:** Acidic soil, indicating a higher concentration of hydrogen ions.
- **pH = 7:** Neutral soil, representing an equal balance of hydrogen and hydroxide ions.
- **pH > 7:** Alkaline (basic) soil, where the concentration of hydroxide ions exceeds that of hydrogen ions.

The pH level of soil is crucial because it governs the solubility and chemical forms of many essential nutrients and minerals, thereby directly influencing their availability to plants. A slightly acidic to neutral pH range (approximately 6.0–7.0) is generally considered optimal for most crops, as it ensures maximum availability of macro- and micronutrients. However, different plant species exhibit distinct pH preferences, which makes soil pH management a critical component of diversified and sustainable agricultural systems [12, 14]. Owing to its central control over nutrient dynamics, microbial activity, and root growth, soil pH is rightly regarded as a master variable in soil fertility and crop productivity.

4. Factors Affecting Soil pH

Soil pH is influenced by a combination of natural processes and human interventions. Understanding these factors is essential for effective soil management in agricultural and horticultural systems.

4.1 Parent Material

The mineral composition of the parent material plays a major role in determining inherent soil pH. Soils derived from limestone or basalt are generally alkaline, whereas those formed from granite or sandstone are often acidic [7, 11]. The presence of specific minerals such as iron, aluminium, and calcium further influences soil reaction. Soils rich in calcium carbonate (lime) typically exhibit higher pH values, while soils with high organic matter content often tend toward lower pH due to organic acid formation during decomposition [8, 10].

4.2 Climate

Climate, particularly rainfall and temperature, strongly affects soil pH. In regions with high rainfall, basic cations such as calcium and magnesium are leached from the soil profile, resulting in progressive acidification. Additionally, rainfall may contribute acidic compounds derived from atmospheric sources, further lowering soil pH [9, 16]. Temperature also influences microbial activity and organic matter decomposition. In tropical climates, where decomposition rates are high, soils often become more acidic due to rapid production of organic and inorganic acids [18, 19].

4.3 Human Activities

Human interventions significantly modify soil pH, especially under intensive agricultural systems.

- **Fertilizers and amendments:** The long-term use of nitrogenous fertilizers, particularly ammonium-based fertilizers, promotes soil acidification through nitrification processes. In contrast, the application of lime is a common practice to raise soil pH and ameliorate soil acidity [12, 17].
- **Irrigation:** Excessive irrigation, especially with saline or sodic water, can increase soil pH and induce alkalinity, whereas poor drainage conditions may enhance acidification processes [20, 25].
- **Agricultural practices:** Continuous monocropping, intensive tillage, and flooding practices can alter soil pH. For example, rice paddies maintained under submerged conditions often develop more acidic environments due to anaerobic decomposition of organic matter and associated biochemical reactions [21, 13].

4.4 Biological Activity

Soil organisms, including bacteria, fungi, and earthworms, play an important role in regulating soil pH. The decomposition of organic matter by microorganisms releases organic acids, which can lower soil pH over time [22, 24]. In addition, nitrogen-fixing bacteria associated with legumes can influence soil pH through the production and transformation of nitrogenous compounds, contributing to soil acidification under certain conditions [23, 26]. Thus, biological processes act both as drivers and regulators of soil pH dynamics.

5. Soil pH and Its Relationship with Soil Chemistry

Soil pH is closely linked to soil chemical reactions, particularly those governing nutrient solubility, ion exchange, and microbial-mediated transformations. The pH level controls the dissociation of chemical compounds in the soil solution and, consequently, the availability of essential nutrients to plants [35, 37].

5.1 Nutrient Availability

- **Acidic soils (pH < 6):** In acidic conditions, elements such as iron, manganese, and aluminium become more soluble and may reach toxic concentrations for plants if excessively accumulated [28, 34]. At the same time, the availability of essential base cations such as calcium, magnesium, and potassium is reduced, which can limit plant growth.
- **Alkaline soils (pH > 7):** Under alkaline conditions, nutrients such as iron, zinc, and phosphorus become less soluble and less available to plants, often resulting in widespread micronutrient deficiencies, particularly in soils with pH above 8.0 [29, 33].
- **Neutral soils (pH 6–7):** This range is generally considered optimal for most crops, as it (ensures) balanced availability of major nutrients such as nitrogen, phosphorus, and potassium, along with trace elements like copper, zinc, and manganese [30, 32].

These relationships clearly demonstrate why soil pH is a key regulator of soil fertility and crop productivity.

5.2 Soil Microbial Activity

Soil microorganisms, including bacteria, fungi, and earthworms, play crucial roles in nutrient cycling, organic matter decomposition, and soil structure formation. These organisms are highly sensitive to soil pH, and each group exhibits specific pH optima for growth and activity [31, 36]. For instance, nitrogen-fixing bacteria generally perform best in neutral to slightly acidic soils, whereas many decomposer fungi prefer mildly acidic conditions [37, 38]. Consequently, changes in soil pH can alter microbial community structure and function, leading to cascading effects on nutrient availability, soil health, and plant growth [38, 39].

5.3 Soil Buffering Capacity

Soil buffering capacity refers to the ability of soil to resist changes in pH when acidic or alkaline substances are added. Soils rich in clay and organic matter typically exhibit high buffering capacity due to their greater cation exchange capacity and reactive surfaces, allowing them to maintain relatively stable pH over time [40, 43]. In contrast, sandy soils with low organic matter content have low buffering capacity and are more prone to rapid pH fluctuations in response to fertilizers, irrigation water, or atmospheric deposition [42, 44]. Buffering capacity, therefore, plays a critical role in determining the stability of soil pH and the effectiveness of soil pH management strategies.

6. Soil pH and Its Influence on Plant Growth

Soil pH plays a crucial role in determining plant health and productivity by regulating nutrient availability, microbial activity, and the overall soil chemical environment. An optimal soil pH ensures efficient nutrient uptake, supports beneficial microbial communities, and promotes healthy root development. Consequently, understanding the influence of soil pH on plant growth is essential for effective soil management and sustainable agricultural production [41, 45]. This section discusses the effects of soil pH on nutrient uptake, microbial dynamics, root function, and overall plant performance [46, 48].

6.1 Nutrient Availability and Uptake

Soil pH strongly influences the solubility and chemical form of nutrients in soil, thereby determining their availability to plants. Each nutrient responds differently to changes in pH, and these interactions directly affect plant growth and yield [47, 49].

6.1.1 Acidic Soils (pH < 6.0)

In acidic conditions, elements such as aluminium, manganese, and iron become more soluble. Although some of these elements are essential micronutrients, their excessive solubility may lead to toxicity, particularly aluminium and manganese, which can damage root systems and restrict plant growth [50, 52]. At the same time, the availability of essential nutrients such as calcium, magnesium, and phosphorus decreases due to increased fixation and reduced solubility, often resulting in nutrient deficiencies and poor crop performance [51, 54].

6.1.2 Alkaline Soils (pH > 7.0)

In alkaline soils, the solubility of several micronutrients, including iron, zinc, copper, and manganese, is markedly reduced, leading to frequent deficiency symptoms in crops [53, 59]. Phosphorus availability is also adversely affected under alkaline conditions, as it tends to form insoluble compounds with calcium and magnesium, thereby limiting its uptake by plants and negatively influencing root development and energy metabolism [54, 58].

6.1.3 Neutral Soils (pH 6.0–7.0)

Neutral to slightly acidic soils generally provide the most favourable conditions for plant growth, as the majority of essential nutrients—including nitrogen, phosphorus, potassium, calcium, magnesium, and micronutrients—are present in forms that are readily available for plant uptake. This explains why most agricultural crops perform best within this pH range [55, 57].

6.2 Impact of Soil pH on Microbial Activity

Soil microorganisms play a vital role in nutrient cycling, organic matter decomposition, and the maintenance of soil structure. These organisms are highly sensitive to soil pH, and even small changes in pH can significantly alter microbial community structure and function [56, 61].

6.2.1 Microbial Diversity and Function

Soil pH regulates both the diversity and activity of microbial populations. Nitrogen-fixing bacteria generally perform best in neutral to slightly acidic soils, whereas many decomposer fungi prefer mildly acidic conditions [59, 60]. In strongly acidic soils, microbial diversity may decline, and the activity of beneficial organisms involved in nutrient cycling may be suppressed [57, 62]. Similarly, in alkaline soils, the activity of many beneficial microbes is constrained due to nutrient limitations and unfavorable chemical conditions, which can reduce nutrient cycling efficiency and overall soil health [63–69].

6.2.2 Soil-Borne Diseases

Soil pH also influences the incidence and severity of soil-borne diseases. Certain pathogens thrive under specific pH conditions, whereas others are inhibited. For example, some Fusarium species are more prevalent in slightly alkaline soils. Maintaining soil pH within an optimal range can therefore help suppress pathogenic organisms and reduce disease pressure in crops [64, 67].

6.3 Root Function and Soil pH

Root growth and function are strongly influenced by soil pH, as pH affects both soil chemical properties and the rhizosphere environment.

6.3.1 Root Growth and Development

In strongly acidic soils, increased solubility of toxic elements such as aluminium can damage root cells, inhibit root elongation, and reduce the plant’s capacity to absorb water and nutrients [67, 68]. In alkaline soils, nutrient imbalances and micronutrient deficiencies can impair root function and limit water uptake [57, 61]. In contrast, neutral soils generally provide the most favourable conditions for root growth due to balanced nutrient availability and minimal toxic element interference [65, 72].

6.3.2 Water and Nutrient Uptake

Soil pH influences the efficiency of water and nutrient absorption by plant roots. Under highly acidic or alkaline conditions, nutrient imbalances and root damage may restrict uptake processes, whereas in neutral soils, both water and nutrients are absorbed more efficiently, supporting vigorous plant growth and higher productivity [70, 73].

6.4 Soil pH and Overall Plant Health

Beyond nutrient availability and microbial activity, soil pH also affects plant tolerance to environmental stresses and resistance to diseases [42, 49]. In strongly acidic soils, plants often suffer from nutrient deficiencies, metal toxicity, and poor root development, which may manifest as chlorosis, stunted growth, and reduced biomass accumulation [47, 49]. Similarly, in alkaline soils, limited availability of micronutrients such as iron and zinc frequently results in chlorosis, poor growth, and reduced yield [71, 74]. In contrast, soils with near-neutral pH generally provide a stable and balanced environment that supports optimal plant health and productivity [66, 67]. Furthermore, plants grown under optimal pH conditions tend to exhibit greater resistance to diseases, whereas pH-induced nutrient stress can weaken plant defence mechanisms and increase susceptibility to pathogens [5, 47, 75].

7. Optimal Soil pH for Different Crops

Different crops exhibit distinct pH preferences that influence their growth, nutrient uptake, and yield potential. Although most crops perform best in slightly acidic to neutral soils (pH 6.0–7.0), some species are adapted to more acidic or more alkaline conditions. Understanding these requirements is essential for optimizing soil management and crop productivity [47, 49].

8. Managing Soil pH for Optimum Plant Growth

Proper soil pH management is essential for sustaining crop productivity and preventing nutrient imbalances or toxicities. This involves regular soil testing, appropriate amendment strategies, and long-term monitoring [47, 52].

9. Effects of Soil pH on Soil Microbial Populations

Soil pH is a dominant factor controlling microbial diversity, activity, and nutrient cycling processes. Neutral to slightly acidic soils generally support the most diverse and active microbial communities, promoting efficient nitrogen fixation, phosphorus solubilization, and organic matter decomposition [7, 19, 47, 56]. In contrast, strongly acidic or highly alkaline soils often exhibit reduced microbial diversity, impaired decomposition rates, and disrupted nutrient cycling, ultimately leading to lower soil fertility and reduced crop performance [27, 39, 59].

10. Challenges and Risks in Soil pH Management

Improper pH management can result in over-liming or over-acidification, nutrient imbalances, delayed crop responses, and adverse environmental impacts. Excessive liming may induce micronutrient deficiencies, whereas excessive acidification can cause metal toxicity and microbial suppression [47, 54, 69]. Moreover, pH amendments often act slowly, creating management challenges under intensive cropping systems [27, 39, 75]. Environmentally, excessive use of amendments may contribute to nutrient leaching, runoff, and increased carbon footprint, highlighting the need for careful, soil-test-based pH management strategies [34, 36, 47, 59].

9. Future Directions in Soil pH Research

Future research is increasingly focused on precision soil pH management, advanced sensing technologies, and understanding the interactions between soil pH and climate change. Real-time pH sensors, integration with precision agriculture tools, and site-specific amendment strategies are expected to improve efficiency and sustainability of soil pH management [45, 52, 56, 67]. Additionally, long-term studies on soil health, carbon sequestration, and the role of organic matter in buffering pH fluctuations will be crucial for developing resilient and climate-smart agricultural systems [34, 36, 64, 66].

10. Management of Soil pH

10.1. Liming

Application of lime materials (e.g., calcium carbonate) to acidic soils raises pH and improves nutrient availability and crop yields. Meta-analyses have shown that liming increases soil pH and yields in a range of cropping systems.

10.2. Acidification and Organic Amendments

For alkaline soils, acidifying fertilizers and organic amendments can help moderate pH over time. Organic amendments also enhance soil structure and microbial health, improving nutrient cycling.

10.3. Precision Management

Site-specific soil testing and variable rate amendment application allow efficient management of pH spatial variability within fields, optimizing nutrient availability and crop performance across landscapes.

11. Challenges and Future Directions

Although the optimal pH range for most crops lies between 6.0 and 7.0, soils often fall outside this range due to parent material, climate, and management practices. Future research should aim to:

- Develop better pH monitoring tools,
- Breed crop varieties tolerant of pH extremes,
- Integrate precision amendment strategies with climate-smart agriculture.

The role of soil pH under changing climatic conditions and its interaction with nutrient dynamics remains a key research frontier.

12. Conclusion

Soil pH is a foundational determinant of soil fertility and crop productivity because it regulates nutrient availability, microbial processes, and plant physiological responses. As a true “master variable,” soil pH integrates chemical, biological, and physical aspects of soil functioning and thereby shapes the overall performance of agroecosystems. The evidence reviewed clearly shows that strongly acidic soils are constrained by metal toxicity, reduced base cation availability, and suppressed biological activity, while highly alkaline soils are limited by micronutrient deficiencies and phosphorus fixation. In contrast, neutral to slightly acidic soils provide the most favourable conditions for balanced nutrient supply, active microbial communities, healthy root development, and stable crop yields. Effective soil pH management—through regular soil testing, judicious use of lime or acidifying amendments, incorporation of organic materials, and site-specific precision practices—remains essential for sustaining soil health and improving nutrient use efficiency. However, pH correction must be approached cautiously to avoid over-liming or excessive acidification, which can create new nutrient imbalances and environmental risks. Looking ahead, future research should focus on precision pH management, long-term soil health monitoring, and the interactions between soil pH, climate change, and cropping systems. By maintaining soil pH within an optimal range, farmers and land managers can enhance soil resilience, improve crop productivity, and support the long-term sustainability of agricultural systems.

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