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Soil pH and plant growth: A detailed review of interactions and management

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Abstract
Soil pH is a critical factor in determining soil health, plant growth, and agricultural productivity. It affects the availability of essential nutrients, microbial activity, and overall soil ecosystem dynamics. This review explores the importance of soil pH in plant growth, detailing how it influences nutrient availability, microbial diversity, root function, and plant health. We examine the optimal pH requirements for different crops, as well as the challenges associated with adjusting and managing pH levels. Various methods for testing and adjusting soil pH, including the use of lime, sulphur, and organic amendments, are discussed, alongside best practices for long-term pH management. The review also highlights the impact of soil pH on microbial populations and soil-borne diseases, as well as the risks associated with over-correction and nutrient imbalances. Case studies demonstrate the practical application of soil pH management in agriculture, and future research directions focus on advancements in testing technology, sustainable amendments, and the effects of climate change on soil pH. Overall, understanding and managing soil pH is essential for optimizing soil health, improving crop yields, and fostering sustainable agricultural practices.

Keywords: Soil pH, nutrient availability, microbial activity, pH management, agricultural productivity, soil amendments

1. Introduction
Soil pH is a critical factor influencing soil health, plant growth, and agricultural productivity. It refers to the acidity or alkalinity of the soil, which directly impacts the availability of nutrients, soil microbial activity, and overall plant development. Soil pH is typically measured on a scale from 0 to 14, where values below 7 indicate acidic soil, values above 7 indicate alkaline soil, and values around 7 indicate neutral soil. The pH of the soil affects the solubility of essential nutrients, which in turn affects their uptake by plants. It also plays a vital role in influencing the microbial population and enzymatic activity in the soil [1, 4].

In agricultural practices, understanding and managing soil pH is fundamental to ensuring healthy plant growth and optimizing crop yields. While most plants thrive in neutral to slightly acidic soils (pH 6-7), certain crops have specific pH requirements, making soil pH management critical for successful farming. For example, some crops such as blueberries require more acidic soils, while others like asparagus prefer alkaline conditions [3, 4].

Soil pH also has a profound effect on nutrient availability. In acidic soils, some nutrients, such as iron, manganese, and aluminium, become more soluble, potentially leading to toxicity in plants. Conversely, alkaline soils can result in the deficiency of nutrients such as iron, zinc, and phosphorus, as they become less available to plants. Thus, managing soil pH to maintain the ideal range for plant growth is essential to avoid nutrient imbalances and improve crop productivity [2, 5].

2. Fundamentals of Soil pH
Soil pH is a measure of the hydrogen ion (H^+) concentration in the soil, which indicates the soil's acidity or alkalinity. It plays a vital role in determining soil chemistry, as it affects nutrient availability, microbial activity, and the overall health of the soil ecosystem. Understanding the fundamentals of soil pH is essential for managing soil health and ensuring optimal plant growth. This section delves into the definition, measurement, factors influencing soil pH, and the processes that contribute to soil pH variation [6, 15].

Definition of Soil pH

Soil pH refers to the concentration of hydrogen ions in the soil solution. It is typically measured on a scale of 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 ions and hydroxide ions.
- **pH > 7:** Alkaline (basic) soil, where the concentration of hydroxide ions exceeds that of hydrogen ions.

The pH level of the soil is crucial because it determines the solubility of many essential nutrients and minerals in the soil, directly influencing their availability to plants. For instance, a neutral pH (around 6-7) is generally considered optimal for most plants, as it allows the maximum availability of nutrients. However, different plants have varying pH preferences, which is why managing soil pH is essential for diverse agricultural practices [12, 14].

Factors Affecting Soil pH

Soil pH is influenced by a combination of natural and human-driven factors. Understanding these factors can help in effectively managing soil pH for agricultural and horticultural purposes.

1. **Parent Material**

- The minerals that make up the soil known as the parent material play a significant role in determining the soil's pH. For instance, soils derived from limestone or basalt tend to be more alkaline, while those formed from granite or sandstone are often more acidic [7, 11].
- The presence of specific minerals like iron, aluminium, and calcium can also affect soil pH. Soils rich in calcium carbonate (lime) are typically more alkaline, while soils with high organic matter content often exhibit lower pH levels [8, 10].

2. **Climate**

- Climate factors, particularly precipitation and temperature, have a major influence on soil pH. Rainfall is one of the most significant drivers, as it can leach minerals and nutrients from the soil. In areas with heavy rainfall, soils tend to be more acidic due to the dissolution of acidic compounds like sulfuric acid from the atmosphere [9, 16].
- Warmer temperatures can also affect microbial activity and organic matter decomposition, influencing pH. For example, in tropical climates, where decomposition is rapid, soils tend to be more acidic [18, 19].

3. **Human Activities**

- **Fertilizers and Amendments:** The use of chemical fertilizers, particularly nitrogen-based fertilizers (such as ammonium nitrate), can acidify the soil over time. The addition of lime to soil is a common practice to raise pH levels, especially in acidic soils [12, 17].
- **Irrigation:** Over-irrigation, especially with water that has a high level of dissolved salts (saline water), can raise soil pH, making it more alkaline. Conversely, poor drainage can lead to soil acidification [20, 25].
- **Agricultural Practices:** Continuous monocropping and tilling practices can lead to soil degradation and pH imbalances. For example, rice paddies are often kept flooded, which can lower pH and create more acidic conditions due to the decomposition of organic matter in anaerobic (low oxygen) conditions [21, 13].

4. **Biological Activity**

- The activity of soil organisms, including bacteria, fungi, and earthworms, also affects soil pH. For instance, the decomposition of organic matter by microbes can release organic acids, leading to a decrease in soil pH (soil acidification) [22, 24].
- Nitrogen-fixing bacteria in legume roots can alter soil pH through the production of ammonia, which can be further converted into ammonium ions (NH_4^+), contributing to a decrease in pH [23, 26].

Soil pH and its Relationship with Soil Chemistry

Soil pH is closely linked to the chemical composition of the soil, particularly in terms of nutrient availability and microbial activity. The pH level affects the dissociation of chemical compounds in the soil and, consequently, the solubility of various nutrients [37, 35].

1. **Nutrient Availability**

- **Acidic Soils (pH < 6):** In acidic soils, certain nutrients such as iron, manganese, and aluminium become more soluble and are present in forms that are potentially toxic to plants if they accumulate in high concentrations (28,34). However, other essential nutrients like calcium, magnesium, and potassium become less available for uptake by plants.
- **Alkaline Soils (pH > 7):** In alkaline conditions, nutrients like iron, zinc, and phosphorus become less soluble and harder for plants to access, leading to deficiencies in crops. This is often seen in soils with a pH higher than 8, where micronutrient deficiencies are common [29, 33].
- **Neutral Soils (pH 6-7):** Neutral pH is considered ideal for most plants, as it allows for the optimal availability of a wide range of nutrients, including nitrogen, phosphorus, potassium, and trace minerals such as copper, zinc, and manganese [30, 32].

2. **Soil Microbial Activity**

- Soil microorganisms such as bacteria, fungi, and earthworms play essential roles in nutrient cycling and organic matter decomposition. These organisms are sensitive to changes in soil pH, with each species thriving within specific pH ranges [31, 36].
- For example, nitrogen-fixing bacteria tend to be more effective in neutral to slightly acidic soils, while some species of fungi that help decompose organic material prefer slightly acidic conditions [37, 38].
- The growth and efficiency of soil microorganisms are therefore influenced by pH, which can have a cascading effect on overall soil health and plant growth [38, 39].

3. **Soil Buffering Capacity**

- The buffering capacity of soil refers to its ability to resist changes in pH when acidic or alkaline substances are added. Soils with high buffering capacity, typically those rich in clay or organic matter, can maintain a stable pH over time, even with the addition of amendments [40, 43].
- Soils with low buffering capacity, such as sandy soils, tend to experience more significant pH fluctuations in response to inputs like fertilizers, irrigation, or atmospheric deposition [42, 44].

3. Soil pH and Its Influence on Plant Growth

Soil pH plays a crucial role in determining the health and growth of plants by affecting nutrient availability, microbial activity, and overall soil environment. Understanding how soil pH influences plant growth is essential for managing soil health and ensuring optimal agricultural productivity [41, 45]. This section explores the various ways in which soil pH affects plant growth, focusing on nutrient uptake, microbial dynamics, root function, and overall plant development [46, 48].

Nutrient Availability and Uptake

Soil pH significantly influences the solubility of nutrients in the soil, thereby affecting their availability to plants. Each nutrient behaves differently depending on the pH level of the soil, and this relationship directly impacts plant health and growth [47, 49].

1. **Acidic Soils (pH < 6)**

- **Increased Solubility of Toxic Elements**: In acidic conditions, certain elements like aluminium, manganese, and iron become more soluble. While these elements are essential for plant growth, their excess in acidic soils can lead to toxicity. High concentrations of aluminium and manganese can cause root damage, poor root development, and hinder plant growth [50, 52].
- **Limited Availability of Essential Nutrients**: While some nutrients like iron, manganese, and boron may become more available in acidic soils, others such as calcium, magnesium, and phosphorus tend to precipitate and become less soluble. This reduces their availability for plant uptake, potentially leading to nutrient deficiencies [51, 54].

2. **Alkaline Soils (pH > 7)**

- **Reduced Solubility of Micronutrients**: In alkaline soils, micronutrients like iron, zinc, copper, and manganese become less soluble and thus less available to plants. This can result in nutrient deficiencies, particularly in plants that require these nutrients in small amounts for optimal growth [53, 59].
- **Phosphorus Availability**: Phosphorus, a vital macronutrient for plants, is most available in neutral to slightly acidic soils. In alkaline soils, phosphorus tends to form insoluble compounds with calcium and magnesium, reducing its availability for plant uptake. This can lead to phosphorus deficiency, affecting plant growth and development [54, 58].

3. **Neutral Soils (pH 6-7)**

- **Optimal Nutrient Availability**: Neutral soils typically provide the best conditions for nutrient availability. In this pH range, the majority of essential nutrients, including nitrogen, phosphorus, potassium, calcium, magnesium, and trace elements, are in their most soluble and available forms for plant uptake. This is why most plants grow best in neutral to slightly acidic soils [55, 57].

Impact on Soil Microbial Activity

Soil microorganisms, including bacteria, fungi, and other microbes, are essential for nutrient cycling, organic matter decomposition, and maintaining overall soil health. These microorganisms are highly sensitive to changes in soil pH, and their activity is directly influenced by the pH level [56, 61].

1. **Microbial Diversity and Function**:

- Soil pH influences the diversity and abundance of microbial populations. For example, bacteria that promote nitrogen fixation tend to be more active in slightly acidic to neutral soils. In contrast, some fungi, which are important for decomposing organic material and forming symbiotic relationships with plants, thrive in slightly acidic soils [59, 60].
- **Acidic Soils**: Acidic conditions may reduce the diversity of soil microorganisms, particularly those involved in nitrogen fixation and organic matter breakdown. Acid-loving (acidophilic) bacteria may dominate, but beneficial microbes essential for nutrient cycling may be suppressed [57, 62].
- **Alkaline Soils**: In alkaline soils, the activity of many beneficial microbes may be limited due to nutrient deficiencies and the less favourable pH environment. This can disrupt soil health and reduce nutrient cycling efficiency [63-69].

2. **Soil-borne Diseases**

- Soil pH can also impact the prevalence of soil-borne diseases. Some pathogenic organisms, like certain species of fungi and bacteria, thrive in either acidic or alkaline conditions, while others are more sensitive to pH changes. For example, Fusarium species, which cause root rot, are more common in slightly alkaline soils. Thus, maintaining a balanced soil pH helps control soil-borne pathogens and diseases [64, 67].

Root Function and Soil pH

Root development and function are strongly influenced by soil pH, as pH affects both the chemical properties of the soil and the microbial environment around the roots.

1. **Root Growth and Development**

- **Acidic Soils:** In highly acidic soils, the increased solubility of toxic elements such as aluminum can cause damage to root cells, leading to poor root growth. This reduces the plant's ability to absorb water and nutrients, stunting overall growth [67, 68].
- **Alkaline Soils**: Alkaline soils may not allow adequate nutrient uptake due to the reduced availability of essential micronutrients. Additionally, high pH can cause nutrient imbalances that affect root function and water absorption [57, 61].
- **Neutral Soils**: Neutral pH provides the best environment for root growth, as essential nutrients are readily available, and there are fewer toxic elements that can interfere with root function [65, 72].

2. **Water and Nutrient Uptake**

- Soil pH influences how well plants can access water and nutrients from the soil. In acidic or alkaline conditions, root systems may struggle to access essential nutrients, and water uptake may be impaired due to imbalanced nutrient levels [70, 73].
- In neutral soils, water and nutrients can be absorbed efficiently, allowing plants to grow robustly and remain healthy [72, 73].

Soil pH and Plant Health

Soil pH affects many aspects of plant health beyond just nutrient availability and microbial activity. It also influences the plant's ability to adapt to environmental stressors and its overall resistance to diseases [42, 49].

1. **Plant Stress and pH Imbalances**

- **Acidic Soils:** In soils with very low pH, plant stress can increase due to nutrient deficiencies, metal toxicity, and poor root development. Certain plants may exhibit symptoms like chlorosis (yellowing of leaves) and poor growth as a result of these imbalances [47, 49].

- **Alkaline Soils:** Similarly, in alkaline soils, plants may show signs of nutrient deficiencies, such as stunted growth, leaf yellowing, or poor fruiting, particularly due to the reduced availability of micronutrients like iron and zinc [71, 74].
- **Neutral Soils:** Neutral soils are generally the most conducive to plant health, as they maintain balanced nutrient levels and provide a stable environment for plant roots [66, 67].

2. **pH and Disease Resistance**

- Plant resistance to diseases can be influenced by soil pH. For instance, plants grown in soils with an optimal pH range are often more resilient to stress and disease because their nutrient needs are met and their root systems are healthy [5, 49].
- pH imbalances, on the other hand, can weaken plants and make them more susceptible to pathogens. For example, nutrient deficiencies caused by improper pH levels may weaken plant defences, making it easier for fungi or bacteria to invade [47, 75].

4. Optimal Soil pH for Different Crops

Different crops have distinct pH preferences that influence their growth, nutrient uptake, and overall health. While most plants thrive in neutral to slightly acidic soils (pH 6-7), some crops are better suited to more acidic or more alkaline soils. Understanding the specific pH needs of various plants is essential for optimizing soil conditions and ensuring successful crop production. This section explores the pH preferences of different crops, highlighting the impact of soil pH on crop yields and quality [47, 49].

General pH Requirements for Crops

Most plants grow best within a specific pH range, usually between 5.5 and 7.5. However, slight variations in pH preferences are observed depending on the species. It is essential to understand the general pH requirements for a variety of crops to ensure that soil conditions are optimized for their growth [47, 49].

Vegetables

- **Most vegetables:** Crops such as tomatoes, lettuce, carrots, and cucumbers generally thrive in slightly acidic to neutral soils, with a pH range of 6.0 to 7.0. In this range, most nutrients are readily available, allowing for optimal growth [47, 75].
- **Root vegetables**: Root crops like potatoes and beets prefer slightly acidic soils (pH 5.5-6.5) to enhance root development and prevent common diseases like scab, which thrives in alkaline conditions [47, 49].

Fruits

1. **Berries:** Fruits like blueberries, strawberries, and raspberries prefer more acidic soils (pH 5.5-6.0). Blueberries, in particular, are highly sensitive to soil pH, and when grown in alkaline soils, they experience nutrient deficiencies and poor growth [74, 75].

- **Citrus fruits**: Oranges, lemons, and grapefruits thrive in slightly acidic soils (pH 5.5-6.5), while still tolerating a slightly higher pH (up to 7.0). Soil pH levels outside this range can affect the availability of essential nutrients like iron and magnesium [42, 47].

Legumes

- **Peas, beans, and lentils:** These crops prefer slightly acidic to neutral soils, typically with a pH of 6.0 to 7.0. Legumes have a unique ability to fix nitrogen in the soil, and a balanced pH supports the nitrogen-fixing bacteria involved in this process [17, 23].

2. **Grains and Cereals**

- **Wheat, corn, and rice:** These staple crops generally prefer neutral to slightly alkaline soils (pH 6.0-7.5). Corn, for example, can tolerate slightly higher pH levels, but soil pH above 7.5 can lead to nutrient deficiencies, especially of micronutrients like zinc and iron [27, 29].
- **Rice:** Rice is typically grown in flooded fields, where the pH tends to be slightly acidic (5.5-6.5). Flooding the soil creates anaerobic conditions, which can affect nutrient availability and root health [7, 19].

3. **Herbs and Spices**

- **Basil, thyme, rosemary, and oregano**: Most herbs and spices thrive in slightly acidic to neutral soils, typically with a pH range of 6.0 to 7.5. Herbs like basil and oregano perform best in moderately acidic soils that prevent root diseases and support the development of essential oils in their leaves [47, 49].

Acid-loving Plants

Certain plants, known as acidophiles, prefer highly acidic soils (pH < 6.0). These plants are adapted to thrive in environments with lower pH levels, and their root systems can efficiently absorb nutrients even in the presence of high concentrations of certain minerals that are toxic to other plants [7, 9].

1. **Blueberries:** Blueberries are well-known acid-loving plants that require soils with a pH between 4.5 and 5.5. They are highly sensitive to alkaline soils, which can lead to chlorosis (yellowing of leaves) due to the reduced availability of iron [37, 49].
2. **Azaleas and Rhododendrons:** These ornamental plants prefer acidic soils (pH 5.0-5.5), which promote lush foliage and vibrant blooms. In alkaline soils, they are prone to nutrient deficiencies, particularly of iron and manganese [23, 49].
3. **Cranberries:** Like blueberries, cranberries thrive in highly acidic soils (pH 4.5-5.5). These low pH conditions help minimize competition from other plants and allow the cranberries to access nutrients effectively [47, 42].

Alkaline-loving Plants

Some plants, known as alkaliphiles, prefer or tolerate alkaline soils (pH > 7.0). These plants have adapted to thrive in environments with higher pH levels, where certain essential nutrients may be less soluble and harder for other plants to absorb [5, 25].

1. **Asparagus:** Asparagus is a hardy perennial that thrives in slightly alkaline soils, with a preferred pH range of 7.0 to 8.0. Alkaline conditions promote healthy growth and prevent the spread of soilborne diseases [47, 67].
2. **Spinach:** Spinach prefers slightly alkaline soils with a pH between 6.5 and 7.5. In this range, nutrients like phosphorus and magnesium are readily available, supporting healthy plant growth [47, 65].
3. **Cabbage and Broccoli:** These cruciferous vegetables grow best in slightly alkaline to neutral soils (pH 6.5-

7.5), where they can access ample nutrients like nitrogen, potassium, and calcium [47, 69].

Impact of pH on Crop Yield

Soil pH has a direct effect on crop yield and quality. When soil pH is outside the optimal range for a particular crop, it can lead to nutrient imbalances, poor root development, and reduced plant vigor, all of which contribute to decreased yields [7, 49].

1. **Low pH (Acidic Soils):** In soils with pH levels below the optimal range, plants may experience nutrient deficiencies (e.g., calcium, magnesium, phosphorus) and toxicity (e.g., aluminium, manganese). In severe cases, plants may fail to thrive, leading to reduced crop yields. Acidic soils may also cause poor root development, which impairs water and nutrient absorption [47, 69].
2. **High pH (Alkaline Soils)**: Alkaline soils can result in nutrient deficiencies, particularly of iron, zinc, and manganese. These micronutrients become less available at high pH, leading to chlorosis and stunted growth. High pH also limits phosphorus availability, which can result in poor root development and decreased plant Vigor [47, 49].
3. **Balanced pH:** Crops grown in soils with pH levels within the optimal range for that particular species can access a wide range of nutrients, leading to healthy growth, improved resilience to environmental stress, and higher yields. Maintaining the correct pH balance is, therefore, crucial for maximizing crop production and ensuring high-quality produce [47, 59].

5. Managing Soil pH for Optimum Plant Growth

Proper management of soil pH is essential to ensure that crops can grow healthily, achieve optimal yields, and avoid nutrient imbalances or toxicity. Adjusting soil pH involves both testing and amending the soil to maintain the ideal pH range for specific crops. This section delves into the methods for testing soil pH, strategies for adjusting pH levels, and best practices for long-term soil pH management [47, 52].

Testing Soil pH

The first step in managing soil pH is to accurately measure it. Regular soil pH testing helps determine whether the soil is too acidic, alkaline, or within the optimal pH range for a particular crop. There are several methods for testing soil pH, ranging from simple DIY kits to laboratory-based analysis.

1. Soil pH Meters

Portable pH Meters: Soil pH meters are handheld devices that provide immediate results. They are easy to use and provide relatively accurate readings of soil pH when inserted into a moist soil sample. Many modern meters are designed for both soil and water testing [71, 74].

2. Soil Test Kits: Available in garden centers and online, soil test kits usually come with test strips or colour indicators that change based on the soil's pH level. These kits provide quick, inexpensive results but are less precise than digital pH meters [47, 49].

3. Laboratory Testing: For the most accurate results, soil samples can be sent to a professional soil testing laboratory. Laboratory tests not only measure soil pH but also provide additional information about nutrient levels, organic matter content, and other important soil characteristics. This method is especially useful for large-scale agricultural operations or when managing soil over an extended period [57, 59].

4. Interpreting Soil pH Results: Soil pH results are typically reported on a scale from 0 to 14, with values below 7 indicating acidity and values above 7 indicating alkalinity. For most crops, a pH of 6.0 to 7.0 is considered optimal. Based on the results, decisions can be made regarding pH adjustments and the need for amendments [73, 75].

Adjusting Soil pH

Once soil pH is tested and determined to be outside the optimal range for a particular crop, adjustments can be made. The approach to adjusting pH depends on whether the soil is too acidic or too alkaline. Here are the most common methods for raising or lowering soil pH:

1. Raising Soil pH (Making Soil More Alkaline)

Adding Lime: The most common method for raising soil pH in acidic soils is the application of lime (calcium carbonate). Lime reacts with soil acids to neutralize them, raising the pH. Dolomitic lime, which also provides magnesium, is used in soils deficient in this element.

- **Application Rate**: The amount of lime needed depends on the soil's current pH, the desired pH level, and soil type (e.g., clay, sandy, loam). Generally, it takes around 50 pounds of lime per 1,000 square feet to raise the pH of slightly acidic soils by 1 point.
- **Effectiveness**: Lime is slow-acting, and its effects may take several months to manifest, particularly in clay-heavy soils.
- **Wood Ash**: Wood ash is another material that can raise soil pH. It contains calcium carbonate and other alkaline compounds. However, its effect is not as long-lasting as lime and may need to be reapplied more frequently [37, 45].
- **Bone Meal**: Bone meal, which contains calcium phosphate, can also be used to raise pH slightly, especially in soils that require additional phosphorus [47, 59].

2. Lowering Soil pH (Making Soil More Acidic)

Adding Sulphur: To lower soil pH, elemental sulphur is often used. When applied to soil, sulphur is converted by soil bacteria into sulfuric acid, which reduces the pH [47, 49].

- **Application Rate:** The amount of sulphur needed depends on the soil's initial pH, desired pH, and the soil's texture. For example, sandy soils require less sulphur to lower pH than clay soils. Typically, around 1 to 2 pounds of sulphur per 100 square feet is applied to reduce soil pH by one unit [56, 69].
- **Peat Moss:** Adding organic matter such as peat moss can help acidify the soil. Peat moss not only lowers the pH but also improves soil structure and water retention. This method is particularly useful in small garden beds or for container plants [32, 49].
- **Iron Sulphate and Aluminium Sulphate:** These amendments are more soluble and act faster than

elemental sulphur in acidifying the soil. They are particularly effective for plants that need lower pH levels, such as blueberries.

Adjusting pH with Organic Amendments

- **Organic Matter**: Organic materials like compost, leaf mold, or well-rotted manure can slightly influence soil pH. They generally make soil more acidic due to their decomposition, though their effect on pH is often gradual and subtle. Using organic matter helps improve soil texture, moisture retention, and microbial activity [47, 65].
- **Mulching with Acidic Materials**: Using mulch materials such as pine needles or pine bark can help to gradually acidify the soil as they break down. This method is particularly useful in garden beds planted with acid-loving plants like azaleas or blueberries [4, 54].

Best Practices for pH Adjustment

Adjusting soil pH effectively requires careful planning and application. Here are some best practices to follow when managing soil pH:

1. **Test Soil Regularly**: Soil pH can change over time due to various factors, including rainfall, irrigation, and fertilization practices. It is important to test soil pH regularly to monitor changes and ensure that adjustments are made when necessary [23, 49].
2. **Apply Amendments in the Right Season**: For maximum effectiveness, soil amendments such as lime or sulphur should be applied several months before planting. This allows the amendments time to alter the pH and reach equilibrium in the soil [35, 49].
3. **Avoid Over-correction**: It's important not to over-correct soil pH, as this can lead to nutrient imbalances. For instance, adding too much lime can make soil overly alkaline, leading to deficiencies in iron and other micronutrients. Always follow recommended application rates and guidelines [27, 49].
4. **Incorporate Amendments Evenly**: When applying pH-adjusting amendments, it is crucial to mix them thoroughly into the soil to ensure even distribution. Spot applications may result in uneven pH levels, leading to inconsistent plant growth [17, 49].
5. **Consider the Crop's Needs**: Adjustments to soil pH should be made with consideration for the specific needs of the crops being grown. Some plants require very specific pH levels to thrive, so understanding each crop’s pH preference is key to successful soil management [45, 49].

Long-term Soil pH Management

Managing soil pH is not a one-time task but rather a continuous process that requires long-term planning. Over time, soil pH can fluctuate due to factors such as irrigation, fertilization, and organic matter decomposition. To maintain optimal pH levels, it’s essential to incorporate pH management into overall soil health practices.

1. **Incorporate Organic Matter Regularly**: Organic amendments not only improve soil structure but can also help buffer soil pH. Regularly adding compost or other organic materials helps stabilize soil pH over time and supports healthy soil microorganisms.
2. **Crop Rotation and Cover Cropping**: Rotating crops and using cover crops can improve soil health and stabilize pH. Certain crops, like legumes, can fix nitrogen and affect soil pH, which benefits subsequent crops. Using deep-rooted cover crops also helps improve soil structure and nutrient cycling, indirectly influencing pH [27, 34].
3. **Monitor and Adjust Fertilizer Use**: Excessive or improper use of fertilizers can alter soil pH, especially nitrogen-based fertilizers. It’s important to use fertilizers according to soil test results to avoid unintentional pH changes [47, 49].

6. Effects of Soil pH on soil microbial populations

Soil microorganisms, including bacteria, fungi, and other microbes, play a crucial role in nutrient cycling, organic matter decomposition, and maintaining soil health. These microorganisms are highly sensitive to soil pH, and changes in pH can significantly impact microbial diversity and activity. The interactions between soil pH and microbial populations are critical for soil fertility and overall plant growth. This section explores the relationship between soil pH and soil microorganisms, including the impact of pH on microbial diversity, nutrient cycling, and the suppression of soil-borne diseases [37, 69].

Microbial Diversity and Soil pH

Soil pH strongly influences the diversity and abundance of microorganisms in the soil. Different microbes have varying pH requirements, and each species thrives in specific pH ranges. Soil pH affects the microbial community composition and, consequently, the functionality of the soil ecosystem.

Acidic Soils (pH < 6.0)

1. **Acidophilic Microorganisms:** Acidic soils Favour the growth of acidophilic (acid-loving) microbes. These organisms include certain types of bacteria, fungi, and actinomycetes that are adapted to low pH conditions. For example, nitrifying bacteria involved in the conversion of ammonia to nitrate tend to thrive in slightly acidic to neutral soils, but some species are adapted to acidic conditions [34, 45].
2. **Reduced Diversity:** In highly acidic soils (pH < 5.5), the microbial diversity may decrease due to the toxicity of soluble aluminium and other metals. This reduction in microbial diversity can negatively affect soil health and nutrient cycling, leading to lower fertility and poor plant growth.

Neutral and Slightly Acidic Soils (pH 6.0-7.0)

1. **Optimal Microbial Activity:** Soils with pH values in the neutral range (6.5-7.0) tend to support the most diverse and active microbial communities. In these soils, both beneficial bacteria (such as nitrogen fixers and decomposers) and fungi (such as mycorrhizal fungi) are abundant, leading to efficient nutrient cycling and organic matter decomposition. This promotes soil fertility and supports plant growth [7, 19].
2. **Nutrient Cycling:** In neutral soils, microbial processes such as nitrogen fixation, phosphorus solubilization, and organic matter breakdown are most effective, which benefits plant health and soil structure.

Alkaline Soils (pH > 7.0)

1. **Alkaliphilic Microorganisms**: Alkaline soils tend to favour the growth of alkaliphilic (alkali-loving) microorganisms. These include certain bacteria and fungi that can thrive in higher pH environments. Alkaline soils can support bacteria involved in

nitrification and organic matter decomposition, but the diversity of other beneficial organisms (such as mycorrhizal fungi) may be reduced [27, 39].

2. **Microbial Stress and Imbalance:** In soils with very high pH (above 8.0), microbial activity often decreases because many soil microbes struggle to adapt to the highly alkaline conditions. This can result in nutrient imbalances, reduced organic matter decomposition, and poor nutrient availability for plants [47, 59].

Soil pH and nutrient cycling

Soil microorganisms are essential for nutrient cycling, which is the process by which essential nutrients are transformed into forms that plants can absorb. Soil pH plays a pivotal role in regulating the activity of soil microbes involved in nutrient cycling processes.

1. Nitrogen Cycle

- Soil pH directly influences the activity of nitrogen-fixing bacteria (such as Rhizobium), which help convert atmospheric nitrogen into a form that plants can use. These bacteria are more active in slightly acidic to neutral soils. In acidic soils, the availability of nitrogen may be hindered, while in alkaline soils, nitrogen-fixing bacteria may be less efficient [47, 56].
- In alkaline soils, the nitrification process (conversion of ammonia to nitrate by nitrifying bacteria) may slow down, leading to nitrogen deficiency in plants.

2. Phosphorus Solubilization

- Phosphorus is often bound in the soil in forms that are unavailable to plants. Soil pH affects the solubility of phosphorus. In acidic soils, phosphorus tends to form insoluble compounds with aluminium and iron, while in alkaline soils, it forms insoluble compounds with calcium. Microorganisms such as mycorrhizal fungi and phosphorus-solubilizing bacteria can help release phosphorus from these compounds, making it available to plants. However, these microbes are more effective in neutral to slightly acidic soils [47, 54].

Decomposition of organic matter

- Soil pH influences the rate of organic matter decomposition, which is essential for maintaining soil fertility. Decomposers like bacteria and fungi break down organic material, releasing nutrients back into the soil. In neutral soils, microbial decomposers are most active, while in acidic or alkaline soils, decomposition can be slower due to reduced microbial activity [47, 56].

Sulphur and iron cycling

Sulphur and iron cycles are also influenced by soil pH. In acidic soils, sulphur can be converted into sulphate (SO_4^{2-}), a form that plants can absorb. Similarly, iron is more soluble in acidic soils and becomes more available to plants. In alkaline soils, these nutrients may be less soluble and harder for plants to access.

Soil pH and Soil-Borne Diseases

Soil pH also affects the prevalence of soil-borne diseases. Many pathogens, such as fungi, bacteria, and nematodes, thrive under specific pH conditions, and altering soil pH can suppress or promote their growth. Understanding how pH affects disease dynamics can help in managing soil health and preventing crop losses [47, 53].

1. Fungal Diseases:

- **Acidic Soils:** Certain soil-borne fungal diseases, such as Fusarium wilt, tend to thrive in slightly acidic soils. However, some beneficial fungi, such as arbuscular mycorrhizal fungi (AMF), prefer neutral to slightly acidic soils, where they form symbiotic relationships with plant roots to enhance nutrient uptake [47, 49].
- **Alkaline Soils:** Fungal pathogens like Fusarium oxysporum, which causes wilt diseases, are also prevalent in alkaline conditions. Alkaline pH can promote the growth of these pathogens, especially in crops like tomatoes and peppers.

2. Bacterial Diseases

- Bacterial pathogens, such as those causing root rot or blight, often thrive in alkaline soils. A high pH can enhance the activity of certain soil bacteria, leading to increased risks of diseases like bacterial wilt or soft rot. Conversely, acidic soils can reduce the growth of some harmful bacteria, providing a natural control mechanism [45, 67].

3. Nematode Populations

- Soil pH influences nematode populations, which can cause damage to plant roots. Nematodes tend to thrive in soils with a pH around 7.0, and their populations may decrease in more acidic or alkaline conditions. Adjusting soil pH can, therefore, help manage nematode infestations in crops [34, 44].

Managing Soil pH to Control Microbial Activity

Maintaining a balanced soil pH can help foster a healthy and diverse microbial community in the soil. To promote optimal microbial activity and nutrient cycling, the following strategies can be employed:

1. **Regular Soil pH Testing:** Testing soil pH regularly helps to monitor changes and determine when adjustments are needed to maintain the ideal pH range for both plant growth and microbial health [37, 59].
2. **Adjusting pH with Organic Amendments:** Organic amendments like compost and cover crops can help maintain or slightly adjust soil pH while enriching the soil with organic matter. These amendments promote beneficial microbial populations, improving soil health and nutrient cycling [47, 59].
3. **Use of Biocontrol Agents:** In some cases, beneficial microbes (e.g., mycorrhizal fungi or nitrogen-fixing bacteria) can be introduced to the soil to improve nutrient cycling, suppress soil-borne diseases, and enhance plant health. However, these microbes should be chosen carefully based on the soil's pH and the specific needs of the crops [47, 52].

7. Challenges and Risks in Soil pH Management

While managing soil pH is essential for optimizing plant growth, improving nutrient availability, and ensuring long-term soil health, it comes with its own set of challenges and risks. Improper pH management can lead to nutrient imbalances, soil degradation, and unintended negative effects on plant growth and microbial health. This section explores the key challenges and risks associated with soil pH management, including over-correction, slow responses to amendments, nutrient imbalances, and environmental impact [47, 69].

Over-liming or Over-acidification

One of the most common mistakes in soil pH management is the over-correction of pH levels, either by adding too much lime to raise the pH of acidic soils or using excessive sulphur to lower the pH of alkaline soils.

1. Over-liming (Excess Lime Application)

- **Impact on Soil Nutrients:** Adding too much lime to soil can result in a pH that is too high, which may lead to deficiencies in micronutrients like iron, zinc, and manganese. At high pH levels, these nutrients become less available to plants, potentially causing symptoms of deficiencies such as chlorosis (yellowing of leaves) [47, 54].
- **Soil Imbalances:** Over-liming can also disrupt the balance of calcium and magnesium in the soil. While both elements are essential for plant health, excessive calcium can interfere with the absorption of other vital nutrients, reducing soil fertility.
- **Alkaline Stress on Plants**: Some plants, particularly acid-loving species, are very sensitive to high pH levels. Over-liming may stress these plants, impairing their growth and leading to poor yields or even plant death [57, 69].

2. Over-acidification (Excess Sulphur Application)

- **Nutrient Toxicity:** Excessive acidification can lead to nutrient toxicity, particularly with elements like aluminium and manganese, which become more soluble in highly acidic conditions. High concentrations of these metals can damage plant roots and impair their ability to absorb water and nutrients [37, 49].
- **Soil Erosion**: Over-acidified soils are often more prone to erosion, as the soil structure weakens, and the organic matter content decreases. This can lead to a loss of fertile topsoil, reducing the overall health and productivity of the land.
- **Impact on Soil Microbes**: Extreme acidity can disrupt the activity of beneficial soil microorganisms, particularly those involved in nutrient cycling and organic matter decomposition. This can lead to reduced soil fertility and poor plant growth [47, 49].

Slow Response to pH Adjustment

Soil amendments such as lime and sulphur are slow-acting, meaning that changes in soil pH may take several months or even years to manifest fully, depending on the soil type and the amendment used. This delayed response presents challenges for farmers who need quick results, especially when growing crops with strict pH requirements.

1. Time Lag in pH Changes

1. **Inconsistent Results:** In the interim between applying soil amendments and seeing changes in pH, plants may experience nutrient deficiencies or toxicity, resulting in poor growth or yield. For instance, crops planted immediately after pH adjustments may struggle due to the unavailability of essential nutrients [27, 39].
2. **Seasonal Variability**: Soil pH is influenced by environmental factors such as rainfall, temperature, and organic matter decomposition. These factors can cause pH fluctuations even after amendments have been applied, making it challenging to maintain consistent pH levels year-round [14, 67].
3. **Delayed Correction:** When soil pH is outside the optimal range, it may take time before the plants begin to show visible symptoms of stress. By the time the pH is corrected, significant damage may have already been done, leading to reduced crop yields and potential long-term soil health problems [47, 75].

Nutrient Imbalances

Changes in soil pH can create nutrient imbalances, either by reducing the availability of essential nutrients or by increasing the availability of potentially toxic elements. These imbalances can impair plant growth, reduce crop yields, and lead to nutrient deficiencies or toxicity.

1. Nutrient Deficiencies

1. **In Acidic Soils:** In acidic soils, essential nutrients like calcium, magnesium, and phosphorus become less available, leading to deficiencies that can affect plant growth and development. For example, phosphorus availability decreases as pH drops below 6.0, which is critical for root development and flowering in many crops [47, 49].
2. **In Alkaline Soils:** In alkaline soils, micronutrients such as iron, zinc, and copper become less available, leading to deficiencies that result in chlorosis and poor plant health. Iron deficiency, in particular, is common in alkaline soils and can lead to yellowing of leaves, especially in plants like tomatoes and azaleas [7, 9].

2. Nutrient Toxicity

- **In Acidic Soils:** Excessively acidic soils can lead to the solubility of toxic elements such as aluminium, manganese, and iron. High levels of aluminium in particular can be detrimental to plant roots, preventing proper nutrient uptake and leading to stunted growth and poor crop yields [33, 38].
- **In Alkaline Soils**: Alkaline conditions can increase the availability of toxic elements like calcium and sodium, which can negatively affect plants, particularly those that are sensitive to salt. Excessive calcium can also interfere with the absorption of other nutrients, leading to nutrient imbalances [67, 69].

Environmental Impact of pH Adjustments

Soil pH management can have unintended environmental consequences, especially when amendments such as lime, sulphur, or other chemical fertilizers are applied excessively. Overuse of these amendments can lead to soil and water pollution, as well as harm to local ecosystems [34, 36].

1. Runoff and Leaching

- **Chemical Amendments:** The application of lime or sulphur can cause runoff into nearby water bodies, affecting water quality. For example, excess lime applied to acidic soils may wash into streams and lakes, altering the pH of the water and potentially harming aquatic life. Similarly, sulphur applied to lower soil pH can acidify nearby water sources if runoff occurs [74, 75].

- **Nutrient Leaching:** The application of soil amendments to adjust pH can sometimes lead to the leaching of nutrients or chemicals into groundwater. For instance, excess calcium or magnesium from lime can leach into water supplies, causing nutrient imbalances and pollution [47].

2. Carbon Footprint

- The production and transportation of amendments like lime and sulfur have a carbon footprint, contributing to greenhouse gas emissions. While soil pH management is crucial for plant growth, excessive use of these amendments can add to the environmental burden associated with modern farming practices [47, 59].

3. Impact on soil structure and organisms

- The overuse of pH-altering amendments can affect soil structure, particularly when large amounts of lime or sulfur are applied to rapidly adjust pH. This can lead to soil compaction, reduced microbial diversity, and a decline in soil health over time. For example, excessive lime can reduce soil organic matter content, which is essential for maintaining soil fertility and microbial activity [57, 69].

Best practices to avoid risks and challenges

To mitigate the risks and challenges of soil pH management, the following best practices should be implemented:

1. **Regular Soil Testing**: Soil testing is the most reliable method to monitor pH levels and prevent over or under-correction. Regular testing helps to assess the need for amendments and allows for gradual, controlled adjustments to soil pH [47, 48].
2. **Gradual pH Adjustments**: Rather than applying large amounts of lime or sulfur at once, gradual pH adjustments are recommended. This approach allows for more consistent and long-term changes to soil pH and reduces the risk of nutrient imbalances [47, 49].
3. **Targeted Application**: Amendments should be applied based on crop needs and soil conditions. Applying only the necessary amount of lime, sulfur, or organic amendments can prevent over-correction and reduce the risk of nutrient toxicity or deficiency [47, 49].
4. **Incorporating Organic Matter**: Using organic matter such as compost or cover crops can help buffer soil pH and improve soil structure without the risks associated with chemical amendments. Organic matter also promotes microbial activity, which contributes to nutrient cycling and overall soil health [24, 36].

8. Future directions in soil pH Research

Soil pH plays a fundamental role in soil health, crop productivity, and ecosystem sustainability. While much progress has been made in understanding soil pH and its impact on plant growth, there are still several areas that require further research. Advancements in technology, new soil management practices, and the impact of climate change on soil pH offer exciting opportunities for future research. This section explores the emerging trends and areas of research that hold promise for improving soil pH management and its applications in agriculture [47, 48].

Advancements in Soil pH Testing Methods

As the demand for precision agriculture increases, the need for more accurate, efficient, and accessible soil pH testing methods has grown. Future research in this area focuses on the development of advanced tools and technologies for real-time, high-precision pH measurement, which can help farmers make better-informed decisions [47, 49].

1. Real-time Soil pH Sensors

- **Technology Development:** Research is being conducted on real-time soil pH sensors that can be integrated into irrigation systems, drones, or smart farming tools. These sensors would provide continuous monitoring of soil pH and send data to farmers in real-time, allowing them to make immediate adjustments to fertilizers, irrigation, and soil amendments [47, 52].
- **Benefits:** These sensors would help farmers track pH changes throughout the growing season and respond proactively to pH imbalances. This would minimize the need for labourintensive soil testing and reduce the potential for nutrient deficiencies or toxicities [47, 56].

2. Portable Soil pH Meters:

- **Improved Accuracy and Cost-Effectiveness**: Researchers are working on developing portable, user-friendly soil pH meters that are both accurate and affordable for farmers, especially small-scale growers. These meters could help farmers test multiple locations in their fields quickly and accurately, providing localized pH data for tailored soil management strategies [47, 58].
- **Integration with Other Technologies**: Future soil testing devices may be integrated with other soil monitoring technologies (e.g., moisture, temperature, and nutrient sensors) to provide comprehensive data on soil health and make it easier for farmers to manage soil pH in relation to other factors [47, 67].

Impact of climate change on soil pH

As global climate patterns continue to change, soil pH is likely to be affected by shifts in temperature, precipitation, and organic matter decomposition. Future research will need to address how climate change impacts soil pH and how farmers can adapt to these changes [34, 36].

1. Changes in Soil pH due to climate variability

- **Precipitation and soil acidity:** Increased rainfall in certain regions could lead to more leaching of basic ions like calcium and magnesium from the soil, resulting in increased soil acidity. Conversely, in areas with reduced rainfall or drought, soils may become more alkaline due to the evaporation of water and the concentration of salts [57, 69].
- **Temperature Effects on ph:** Warmer temperatures can influence the rate of microbial activity in the soil, which in turn affects the release of organic acids and the rate of pH changes. In colder climates, reduced microbial activity may slow down the natural acidification or alkalization of soils [7, 19].

2. Adaptation Strategies for Soil pH

- Researchers are exploring strategies to mitigate the effects of climate change on soil pH, such as the use of drought-tolerant crops, organic matter amendments to buffer pH fluctuations, and more precise irrigation management to avoid pH changes caused by over or under-watering [45, 64].

Precision Agriculture and pH Management
The integration of soil pH management with precision agriculture offers the potential to optimize pH adjustments for individual plant needs across different zones of a farm. Advances in data collection, satellite imaging, and automated systems are helping farmers monitor and adjust pH more effectively, ensuring that crops receive the optimal soil conditions for growth [56, 67].

1. Precision Soil pH Adjustment
- **Variable rate application:** Precision farming technologies are enabling variable rate application (VRA) of pH-adjusting amendments. By using GPS and soil mapping technology, farmers can apply lime, sulphur, or other amendments only where needed, reducing waste and improving cost efficiency [45, 55].
- **Field Zoning**: Soil pH varies across large fields, with certain areas being more acidic or alkaline than others. Precision agriculture technologies can identify pH differences within a field and provide targeted recommendations for pH amendments in specific zones, optimizing plant growth and improving overall productivity [47, 49].

2. Integration with other precision technologies
- Soil pH management can be integrated with other precision agricultural tools, such as nutrient management systems, soil moisture sensors and irrigation controllers. This holistic approach allows farmers to manage soil pH in tandem with other factors like nutrient levels, water availability, and pest control, leading to more sustainable and efficient farming practices [34, 36].

Long-term pH management in sustainable agriculture
Long-term soil pH management is essential for maintaining soil fertility and promoting sustainable agricultural practices. Research is focusing on understanding how pH affects soil health over time and developing strategies to maintain balanced pH levels in the long term.

1. Soil Health and pH Maintenance
- Research into soil health emphasizes the role of pH in maintaining a balanced soil ecosystem. Studies are investigating how practices such as organic farming, crop rotation, and cover cropping can help stabilize soil pH and improve soil microbial activity, ultimately supporting long-term soil fertility.
- The role of organic matter in buffering pH fluctuations is a key area of research. Organic amendments can help moderate soil pH by slowly releasing acids or basic compounds, preventing sharp pH shifts that could negatively affect crop growth and soil health [64, 66].

2. Carbon Sequestration and pH
- Soil pH also plays a role in carbon sequestration, as soils with balanced pH levels are more effective at capturing and storing carbon. Research into pH's impact on carbon cycling and greenhouse gas emissions is essential for understanding the role of soil pH in mitigating climate change and promoting sustainable land management practices [34, 66].

9. Conclusion
Soil pH is a fundamental factor influencing plant growth, nutrient availability, and overall soil health. Its management is crucial for optimizing crop productivity, supporting microbial activity, and ensuring sustainable agricultural practices. Understanding the relationship between soil pH and plant health allows farmers to tailor their soil amendments for specific crops, improving yields and reducing nutrient imbalances. While challenges such as over-correction, slow pH adjustments, and nutrient imbalances exist, advances in technology, precision agriculture, and sustainable amendment practices offer promising solutions. Ongoing research into soil pH, its effects on soil ecosystems, and the development of eco-friendly amendments will further enhance our ability to manage pH effectively, promoting long-term soil health and agricultural sustainability.

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