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Examining the adaptability of soil pH to soil dynamics using different methodologies: A concise review

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ABSTRACT

Soil pH is crucial to soil health, influencing nutrient availability, microbial activity, and plant growth. This review aims to assess the adaptability of soil pH under changing soil conditions by analyzing natural and human factors. Information was gathered from various sources, including peer-reviewed articles, field studies, and recent advances in soil science. The study explores how natural factors such as parent material, climate, and vegetation establish baseline soil pH, while human activities such as intensive farming and land-use changes further modify it, often leading to soil acidification or alkalinization. Traditional management methods like lime application, organic amendments, and crop rotation are reviewed for their effectiveness in stabilizing soil pH and their limitations under varying soil conditions. The review also explores modern technological innovations like precision agriculture, which uses soil sensors and variable rate technology for targeted pH management, and biological approaches, such as microbial inoculants, to enhance nutrient cycling and organic matter decomposition. Integrating these traditional and contemporary approaches is essential for sustainable soil pH management and long-term

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productivity. The findings highlight the need for a holistic approach that combines historical knowledge with emerging technologies to promote sustainable agricultural practices and environmental conservation.

1 Introduction

The pH of the soil is a crucial factor that significantly affects its chemical, biological, and physical properties, ultimately determining its suitability for plant growth and overall ecosystem health. Soil comprises mineral particles, organic matter, water, and air, varying proportions based on the type of rock beneath the soil, climate, and land use. The mineral fraction consists of sand, silt, and clay, which determine the soil's texture and affect water retention and nutrient availability. Organic matter, which comes from decomposed plant and animal material, enriches the soil with essential nutrients and improves its structure. The soil's pH is influenced by the interactions among these components and their reaction with various natural and human-induced factors, such as the breakdown of minerals, decomposition of organic matter, and farming practices. Understanding the basic composition of soil and its pH dynamics is essential for effective soil management and sustainable agricultural practices.

A combination of natural and human factors influences soil pH. The type of rock beneath the soil, climate, local vegetation, and farming practices significantly affect soil pH. Additionally, changes in land use, such as urbanization, deforestation, and mining, disrupt the natural soil formation processes and introduce pollutants, altering the soil pH. Understanding these interconnected factors is crucial for effective soil management and sustainable agricultural practices.

The importance of soil pH lies in its direct impact on nutrient availability (Neina 2019). Most essential nutrients are accessible to plants within specific pH ranges (Melese et al. 2015). For example, macronutrients such as nitrogen, phosphorus, and potassium are highly available in soils with a pH range of 6 to 7.5. In contrast, in highly acidic soils (pH < 5.5), the availability of phosphorus and other essential nutrients decreases significantly, leading to nutrient deficiencies that can hinder plant growth and reduce crop yields (Brady and Weil 2008). Conversely, in alkaline soils (pH >7.5), micronutrients such as iron, manganese, and zinc become less available, adversely affecting plant health and productivity (Schmidt and Ellsworth 2000).

Traditional methods for managing soil pH include the application of lime to neutralize acidity and organic amendments like compost and manure to stabilize pH fluctuations (Yenesew et al. 2024). Crop rotation and cover crops can also help maintain balanced soil pH by improving soil structure and increasing organic matter content (Johnston and Goulding 1990; Head 2024). These practices have been used for centuries and are effective in many agricultural systems.

Recent technological innovations have introduced more precise and efficient soil pH management methods. Precision agriculture techniques such as soil sensors and variable rate technology (VRT) enable real-time monitoring and targeted application of soil amendments, which help optimize pH management (Brady and Weil 2008). Biological approaches, including microbial inoculants, are also gaining attention due to their potential to enhance soil health and regulate pH by improving nutrient cycling and organic matter decomposition (McCauley and Jacobsen 2009).

This review aims to comprehensively outline the strategies for effectively managing soil pH under changing environmental and agricultural conditions. It emphasizes combining traditional methods such as lime application, organic amendments, and crop rotation with modern technologies like precision agriculture, soil sensors, and biological interventions. By examining the strengths and limitations of these diverse approaches, the study aims to provide insights into how integrated soil pH management can enhance soil health, optimize plant growth, and contribute to sustainable agricultural practices and environmental conservation. The goal is to equip stakeholders with a nuanced understanding of adaptive soil pH management strategies responsive to natural and human-induced changes, ensuring long-term soil productivity and ecosystem stability.

2 Importance of soil pH

It's crucial to emphasize the significance of soil pH, as it directly influences the availability of vital nutrients for plant growth and their chemical form and solubility. In highly acidic soils with a pH below 5.5, the availability of important nutrients such as phosphorus decreases significantly (Brady and Weil 2008; McCauley and Jacobsen 2009). Additionally, acidic soils can release harmful elements like aluminium and manganese, damaging plant roots and hindering nutrient absorption (Sparks 2003).

The availability of key nutrients such as nitrogen, phosphorus, potassium, iron, manganese, zinc, and copper varies with soil pH (Figure 1). Each nutrient has an optimal pH range where it is most available to plants (Toor and Naeem 2023). Similarly, microbial activity is also affected by pH, being highest around a neutral pH (7.0), indicating that soil microbes are most active and beneficial at this pH level. The shaded area between pH 6 and 7 indicates the optimal pH range for most plant growth, where nutrient availability and microbial activity are generally balanced and favourable (Figure 1).

On the other end of the spectrum, alkaline soils (pH above 7.5) can result in deficiencies of essential micronutrients such as iron, manganese, zinc, and copper. These micronutrients are crucial for various physiological functions in plants, including enzyme activation, chlorophyll synthesis, and maintaining cellular integrity. In alkaline conditions, these nutrients become less soluble and, therefore, less available to plants, leading to symptoms such as chlorosis (yellowing of leaves), reduced growth, and lower crop quality (Schmidt and Ellsworth 2000).

The optimal pH range for most crops lies between 6.0 and 7.5, where the availability of most essential nutrients is maximized, and toxic elements remain insoluble. This range also optimizes microbial activity, which is crucial for organic matter decomposition, nitrogen fixation, and nutrient cycling processes. Microorganisms, like nitrifying bacteria, are also sensitive to pH changes and perform best in slightly acidic to neutral soils. Hence, maintaining soil pH within this optimal range is crucial for sustaining soil fertility and promoting healthy plant growth (Wei et al. 2024).

3 Natural Factors Affecting Soil pH

Several natural factors determine the initial pH of the soil and its changes over time. These include the parent material, climate, and vegetation type. Each factor plays a critical role in shaping the soil's chemical environment and influences its suitability for various plant species and agricultural practices (Wang et al. 2024).

3.1 Parent Material

The mineral composition of the parent material from which soil is formed significantly impacts its pH. Parent material is the underlying geological material (generally bedrock or a superficial or drift deposit) forming soil horizons (Whiteman 2024). The type of minerals present in the parent material largely dictates the initial chemical characteristics of the soil, including its pH. For example, soils that develop from limestone or other calcareous rocks tend to be more alkaline due to calcium carbonate. This compound reacts with water and carbon dioxide to form bicarbonate, which raises the soil pH (Brady and Weil 2008). Conversely, soils derived from acidic parent materials like granite or sandstone typically have a lower pH. Granite, rich in quartz and feldspar, contributes to the formation of acidic soils due to the lack of basic cations like calcium, magnesium, potassium, and sodium (Jing et al. 2024; Subramani et al. 2024). These acidic parent materials make soils more prone to leaching, enhancing their acidity (Sparks 2003). Additionally, the rate of weathering of parent material also influences soil pH. Rapid weathering of certain minerals can release ions that alter the soil's acidity or alkalinity. For instance, the weathering of feldspar minerals releases potassium ions, increasing soil pH, while the breakdown of sulfide minerals can

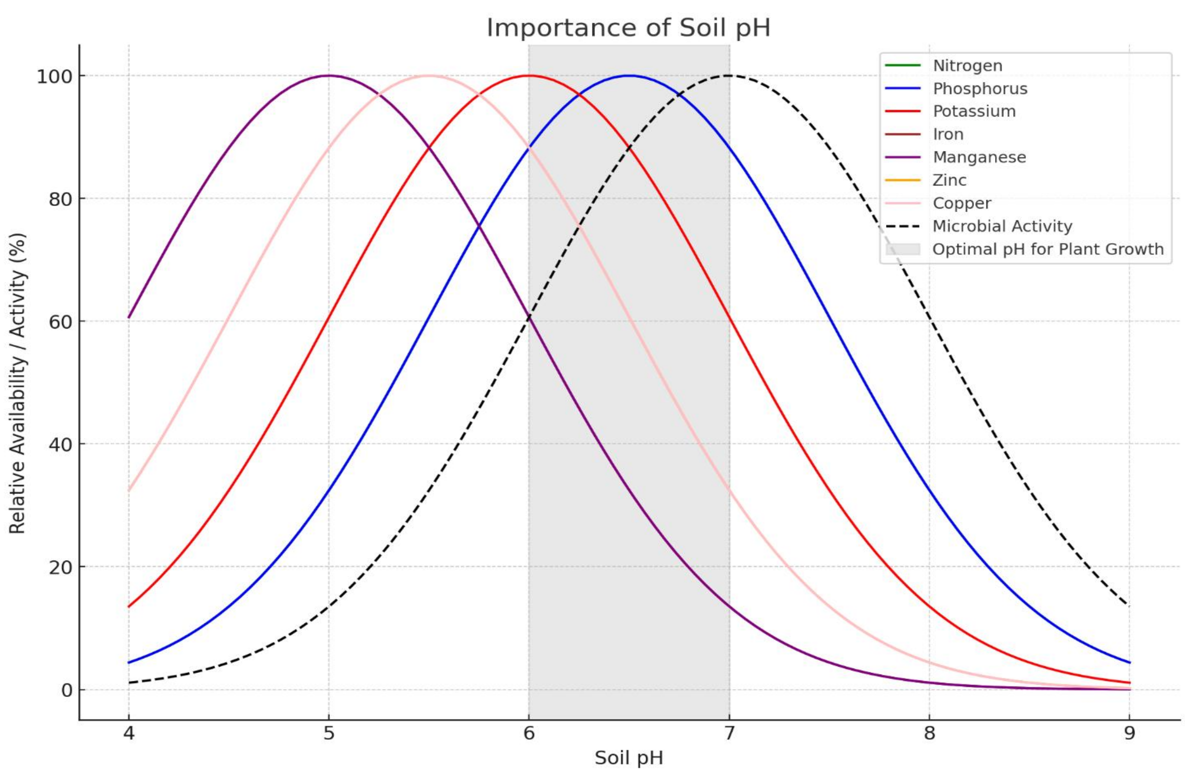

Figure 1 This graph illustrates how soil pH impacts soil health and plant productivity (Based on information from Brady and Weil 2008).

release sulfuric acid, contributing to soil acidity (McCauley and Jacobsen 2009).

3.2 Climatic Conditions

Climatic conditions are another significant factor affecting soil pH, primarily through its influence on weathering processes, leaching, and decomposition of organic matter (Philippot et al. 2024). In regions with high rainfall, acidic conditions are often prevalent. This might be due to the excessive precipitations that lead to leaching, where water percolates through the soil profile and carries away the basic cations such as calcium, magnesium, and potassium. As these cations are leached out, they are replaced by hydrogen ions and aluminium, leading to increased soil acidity (Chatterjee et al. 2024). In contrast, arid and semi-arid regions tend to have more alkaline soils. Limited rainfall reduces leaching, allowing salts and basic cations to accumulate in the soil. These conditions favour the formation of alkaline soils, often characterized by high sodium, calcium, and magnesium carbonate levels. Additionally, the evaporation rate in these regions often exceeds precipitation, concentrating these basic cations in the soil and further increasing alkalinity (Si and Li 2024).

In addition to rain, temperature plays a pivotal role in soil pH dynamics. Warmer temperatures generally enhance the rate of organic matter decomposition and their release, ultimately lowering the soil's pH (Galluzzi et al. 2024). However, in colder climates, slower decomposition rates result in the accumulation of organic matter, which can produce organic acids and contribute to soil acidity over time (Brady and Weil 2008).

3.3 Vegetation Type

The type of vegetation growing on the soil significantly influences its pH through organic matter deposition, root exudation, and nutrient uptake. Different plant species contribute varying amounts and types of organic matter to the soil, and decomposition of these organic matters can raise or lower the soil pH (Yuan et al. 2024). For instance, coniferous forests tend to produce more acidic soils. The needles of coniferous trees, such as pines and spruces, decompose slowly and release organic acids into the soil. These acids contribute to the acidification of the soil, leading to lower pH levels (Mueller et al. 2024). Additionally, the deep root systems of conifers can bring up acidic compounds from deeper soil layers, further contributing to surface soil acidity (Sparks 2003). In contrast, deciduous forests, composed of trees like oaks and maples, lead to the formation of more neutral or slightly acidic soils. The leaf litter from deciduous trees decomposes rapidly and releases fewer organic acids than coniferous needles. This reduces acidification and often more balanced soil pH levels (Joshi et al. 2024).

Grasslands and prairies also impact soil pH differently. The dense root systems of grasses contribute substantial organic matter to the soil, which helps buffer pH changes. Grassland soils often maintain a relatively neutral pH due to the rapid decomposition of organic matter and the cycling of nutrients within the root zone (McCauley and Jacobsen 2009).

4 Anthropogenic factors affecting soil pH

Human activities influence soil pH through agricultural practices, land use changes, and pollution (Figure 2).

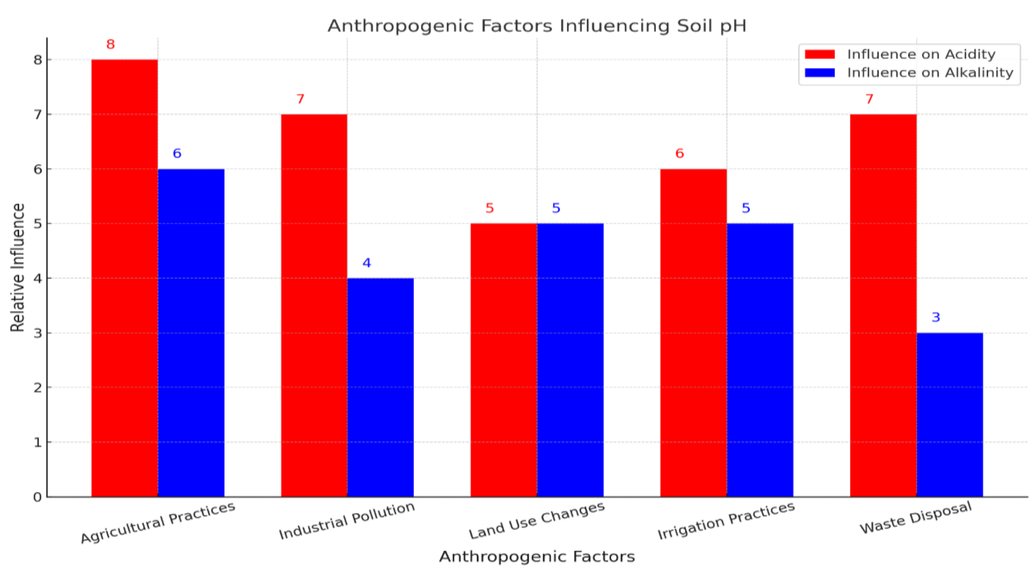

Figure 2 illustrates how each human-induced factor can influence soil pH, leading to either acidity or alkalinity. This figure was created for the current manuscript using data from Brady and Weil (2008).

4.1 Agricultural practices

Agricultural practices such as fertilization, crop rotation, and tillage techniques greatly influence soil pH. Nitrogen fertilizers, especially those containing ammonium, are known for their soil acidification properties. These fertilizers release hydrogen ions during nitrification, lowering soil pH levels (Toor and Ramzan 2023). On the other hand, lime application is a common method to counteract soil acidity and increase pH levels. Lime, usually in calcium carbonate or hydroxide, reacts with hydrogen ions and helps neutralize acidity, promoting a more alkaline soil environment. Crop rotation also plays a significant role in managing soil pH. Certain crops, such as legumes, can fix atmospheric nitrogen through symbiotic relationships with nitrogen-fixing bacteria. This reduces the need for nitrogen fertilizers, thus reducing the risk of soil acidification (Akram et al. 2023). Additionally, tillage practices can impact soil pH by influencing factors such as soil aeration and mixing (Liu et al. 2023; Akram et al. 2023). While these agricultural practices are essential for maintaining soil fertility and crop productivity, careful management is crucial to prevent adverse pH shifts and sustain soil health in the long term.

4.2 Land use changes

Land use changes, including urbanization, deforestation, and mining, disrupt natural soil-forming processes and introduce pollutants that can alter soil pH levels. Urban expansion often results in soil sealing, limiting water infiltration and disrupting soil microbial activity, which affects soil pH (Abakumov et al. 2023). Soil sealing through pavement and construction can lead to localized changes in soil pH, often contributing to increased acidity (Akram et al. 2023). Deforestation reduces organic matter inputs, leading to soil degradation and potential acidification, while mining activities can induce severe soil acidification by releasing acidic compounds such as sulfuric acid. Removing vegetative cover reduces organic matter inputs into the soil and diminishes its buffering capacity against acidity. Additionally, deforestation increases the risk of soil erosion, which can expose acidic subsoil layers, further contributing to soil acidification. The disturbance of soil microbiota and nutrient cycling processes due to forest removal can also impact soil pH dynamics (Tsegaye et al. 2023). Pollution from various sources, including industrial activities and improper waste disposal, can directly contaminate soils with acidic substances, further exacerbating pH imbalances (Wen et al. 2023). Urban areas are sources of various pollutants, including heavy metals and industrial emissions, which can directly acidify the soil or induce chemical reactions leading to pH alterations (Franco-Pesantez and Torres 2023). Mining activities, particularly surface and open-pit mining, also profoundly affect soil pH. Soil disturbance during mining operations exposes acidic subsoil and bedrock materials to the surface, leading to significant soil acidification. Moreover, mining activities often result in acid mine drainage, where sulfuric acid is generated through sulfide minerals oxidizing surrounding soils and waterways (Cao et al. 2024). Chemicals used in mining processes can also contribute to soil acidification through direct contamination and alteration of soil chemistry. Therefore, understanding and mitigating the impacts of these human-induced factors are essential for maintaining soil health and sustaining agricultural productivity in the face of environmental challenges.

5 Approaches to manage soil pH

Various approaches can be used to manage and adjust soil pH under changing conditions, ensuring optimal soil health and productivity (Figure 3).

5.1 Lime application

Lime application is crucial for managing soil pH and creating the best conditions for crop growth. Calcium carbonate ($CaCO_3$) is a commonly used lime source due to its effectiveness in neutralizing soil acidity. Another form of lime, calcium hydroxide ($Ca(OH)_2$), has similar benefits but reacts more quickly with soil acidity, leading to faster increases in pH levels (Charak et al. 2024). This rapid response can be advantageous for crops needing immediate pH adjustments. However, calcium hydroxide is often pricier than calcium carbonate, and its use may result in temporary pH spikes if overused. Careful management is essential to prevent excessive pH fluctuations and maximize its benefits.

Dolomitic lime containing magnesium and calcium carbonate is an effective solution in magnesium-deficient soils. Dolomitic lime raises soil pH and corrects magnesium deficiencies, promoting balanced nutrient availability for plants (Cano-Franco et al. 2024). Overall, lime application, whether in the form of calcium carbonate, calcium hydroxide, or dolomitic lime, is a valuable tool for maintaining soil pH within optimal ranges for crop production. However, proper application rates, timing, and considerations for soil type and crop requirements are essential to maximize its effectiveness while minimizing potential drawbacks.

5.2 Application of appropriate fertilizers

Proper management of fertilizers is crucial for maintaining soil pH balance. Ammonium-based nitrogen fertilizers, commonly used in agriculture, can contribute to soil acidification due to nitrification. During nitrification, soil bacteria convert ammonium ($NH4^+$) into nitrate ($NO3^-$), releasing hydrogen ions (H^+) in the process, which lowers soil pH (Akram et al. 2023). The following methods can be used to manage the acidifying effects of nitrogen fertilizers: (i) Properly managing the application rates and timing of nitrogen fertilizers is crucial. Avoiding excessive nitrogen applications helps minimize the accumulation of ammonium in the soil, reducing the potential for soil acidification, (ii) Utilizing

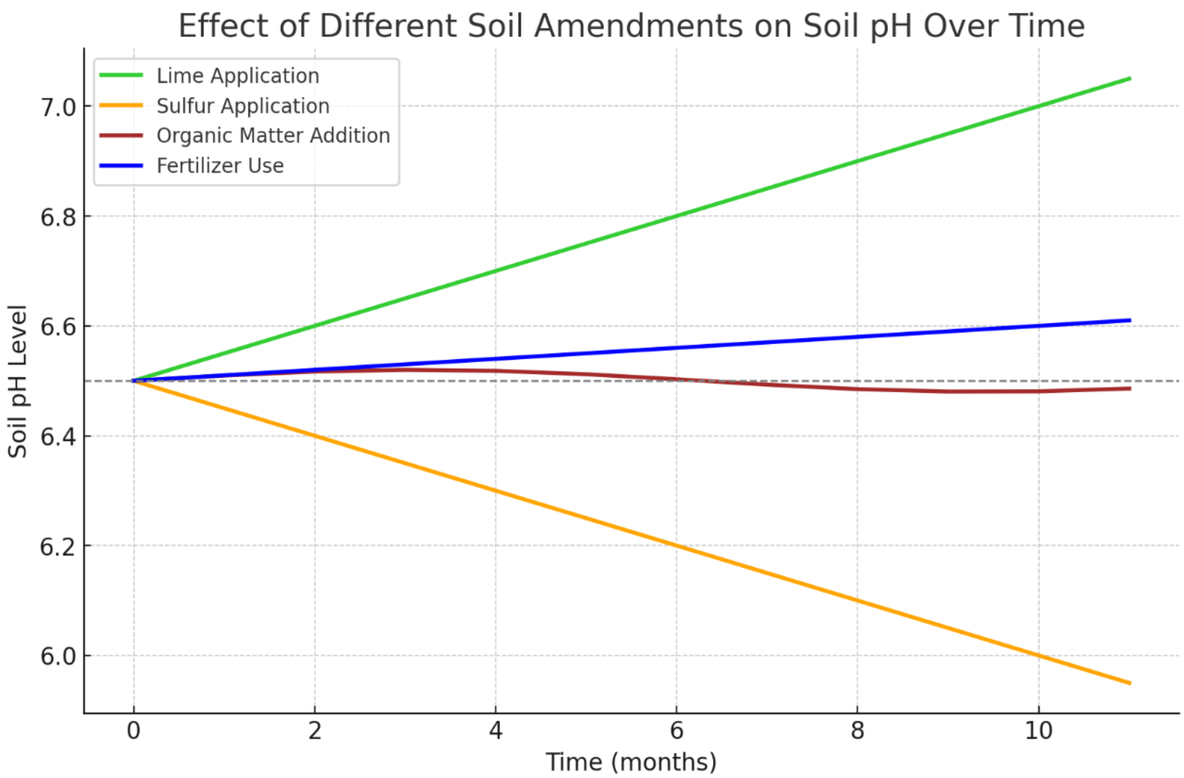

Figure 3 The different approaches can manage soil pH, comparing their effects over one year.

nitrification inhibitors such as nitrapyrin, dicyandiamide (DCD), or 3,4-dimethylpyrazole phosphate (DMPP) can be an effective strategy to slow down the conversion of ammonium to nitrate. These inhibitors work by inhibiting the activity of nitrifying bacteria, thereby reducing the release of hydrogen ions and mitigating soil acidification (Chen et al. 2008), (iii) Choosing nitrogen fertilizers with a higher proportion of ammonium over nitrate can also help minimize soil acidification. Ammonium-based fertilizers release fewer hydrogen ions during nitrification compared to nitrate-based fertilizers, thereby exerting less acidifying pressure on the soil (Chen et al. 2008), (iv) Sulfur-containing fertilizers, such as ammonium sulfate, elemental sulfur, or sulfur-coated urea, can contribute to soil acidification over time through the oxidation of sulfur compounds. Sulfur oxidation produces sulfuric acid, which lowers soil pH. To manage the acidifying effects of sulfur-based fertilizers (Akram et al. 2023), Regularly monitoring soil pH levels helps farmers assess changes over time and detect signs of soil acidification. Timely adjustments to fertilizer management practices can help to prevent or mitigate soil pH imbalances (Lashari 2022), and (vi) Soil buffering capacity should also be considered when using sulfur-based fertilizers. Soils with higher buffering capacity can resist pH changes more effectively, whereas soils with lower buffering capacity are more susceptible to pH fluctuations in response to fertilizer applications (Akram et al. 2023).

5.3 Proper selection of crops and their rotation

Crop selection and rotation strategies are crucial for managing soil pH and promoting overall soil health. By carefully choosing and rotating crops, farmers can enhance nutrient cycling, reduce dependence on fertilizers, and mitigate soil acidification (Mohanty et al. 2024). Two key approaches to crop selection and soil pH rotation incorporate leguminous and deep-rooted crops.

5.3.1 Leguminous crops

Legume crops such as beans, peas, clover, and alfalfa have a special ability to form partnerships with nitrogen-fixing bacteria called rhizobia (Chakraborty 2023). These bacteria live in nodules on the roots of leguminous plants and convert atmospheric nitrogen (N_2) into ammonia (NH_3), which the plants can easily absorb. Farmers can effectively "fix" atmospheric nitrogen by including leguminous crops in crop rotations, reducing the need for synthetic nitrogen fertilizers. This is important because nitrogen fertilizers, especially those containing ammonium, can contribute to soil acidification. Farmers can reduce their reliance on these fertilizers by using legume crops and help mitigate soil acidification (Chakraborty 2023). Additionally, when leguminous crops decompose, they add organic matter to the soil, which improves soil structure and microbial activity, helping to manage pH.

5.3.2 Deep-rooted crops

Certain grasses, grains, and some vegetables have deep root systems that reach into the soil to access nutrients and moisture from lower soil layers (Sharma et al. 2024). These deep-rooted crops can affect soil pH at different depths by reaching deeper soil layers. They play a crucial role in redistributing nutrients, especially those that may have leached below the root zone of shallow-rooted crops. Incorporating deep-rooted crops into crop rotations can help maintain more balanced soil pH profiles throughout the root zone. Additionally, deep-rooted crops contribute to the accumulation of soil organic matter through root turnover and residue deposition, which enhances soil fertility and its ability to resist pH fluctuations (Kumar and Hegde 2023).

5.3.3 Cover crops and Organic amendments

Planting cover crops during fallow periods or between cash crop rotations is an effective strategy for managing organic matter and stabilizing soil pH. Cover crops, such as legumes, grasses, or brassicas, contribute to soil organic matter accumulation through root exudates, root turnover, and aboveground biomass production. As these cover crops decompose, organic matter is incorporated into the soil, enriching soil organic carbon content and enhancing pH buffering capacity (Fageria et al. 2005). Cover crops also play a vital role in nutrient cycling, scavenging residual nutrients from the soil and recycling them upon decomposition. By maintaining soil cover and promoting biological activity, cover crops help sustain soil pH stability, reduce erosion, suppress weeds, and improve soil health (Fageria et al. 2005).

Adding organic materials such as compost, manure, or crop residues to the soil is widely practised to improve soil structure, fertility, and pH buffering capacity. These organic amendments contain various organic compounds that undergo decomposition and release organic acids, which act as buffers against soil acidity, helping to neutralize excess hydrogen ions and mitigate pH fluctuations (Bolan et al. 2023).

Additionally, incorporating organic matter enhances soil aggregation and porosity, improving water retention, nutrient availability, and root penetration. Soils amended with organic matter exhibit greater resilience to pH changes and provide a more favourable environment for plant growth and microbial activity. Soils amended with organic matter can either increase or decrease soil pH, depending on the type of organic matter used and the initial soil conditions. Organic matter, such as compost, manure, or plant residues, generally helps buffer soil pH, making it more resistant to rapid changes. If the organic matter has a high pH (e.g., wood ash), it can increase soil pH, making it more alkaline. Conversely, if the organic matter is more acidic (e.g., peat or certain composts), it can lower the pH, making the soil more acidic. Therefore, the effect on soil pH depends on the specific properties of the organic matter being applied.

Overall, organic matter management through adding organic amendments and using cover crops is essential for maintaining soil pH stability and fertility in agricultural systems (Singh et al. 2024). These practices contribute to long-term soil sustainability by enhancing soil structure, nutrient cycling, and microbial diversity, supporting resilient and productive crop production systems.

6 Technologies used for real-time pH monitoring and management

6.1 Precision agriculture technologies

Precision agriculture technologies provide advanced tools for efficiently and effectively managing soil pH. These technologies

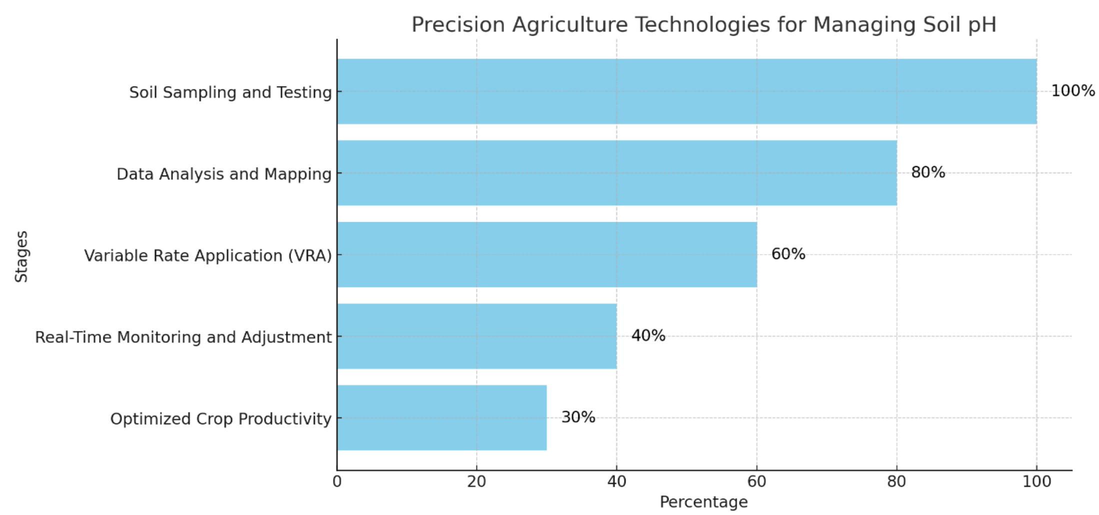

Figure 4 illustrates the progression of precision agriculture technologies from initial soil sampling to optimized crop productivity, showcasing effectiveness and adoption rates at each stage.

optimize crop productivity while minimizing environmental impacts. Two key precision agriculture technologies for soil pH management are Variable Rate Application (VRA) and Soil Sensors and Monitoring Systems (Figure 4).

6.1.1 Variable rate application

The VRA technology allows farmers to apply inputs such as lime and fertilizers at variable rates across fields based on specific soil conditions. This is determined by soil pH maps generated through soil testing (Pawase et al. 2023). By integrating soil pH data into precision agriculture systems, farmers can accurately identify field areas with pH imbalances and adjust lime and fertilizer application rates accordingly. In regions where soil pH varies spatially, VRA ensures that inputs are applied where needed, optimizing pH management, reducing input costs, and minimizing environmental impacts. This targeted approach to soil pH management enhances nutrient use efficiency, reduces the risk of overapplication or underapplication, and promotes more uniform crop growth and yield across fields.

6.1.2 Soil sensors and monitoring systems

Continuous monitoring of soil pH using sensors and monitoring systems provides real-time data on soil pH levels. This enables timely interventions to adjust pH to maintain optimal crop growing conditions (Das et al. 2024). Soil pH sensors can be installed at various depths in the soil profile to monitor changes in pH over time and detect trends or anomalies that may require management action. Additionally, soil pH monitoring systems can be integrated with other precision agriculture technologies, such as automated irrigation systems or crop management software, to facilitate data-driven decision-making and optimize pH management practices (Soussi et al. 2024). By providing insights into soil pH dynamics and trends, soil sensors and monitoring systems empower farmers to implement proactive strategies for pH management, ensuring that crops receive the appropriate pH conditions for optimal growth and productivity.

6.2 Water management

Effective water management, especially irrigation, is essential for regulating soil pH, particularly in areas where water quality can impact pH levels.

6.2.1 Irrigation water quality influence

The quality of irrigation water, including its pH, mineral content, and salinity, can directly influence soil pH. In areas with alkaline water sources, irrigation water may naturally have a high pH due to high concentrations of dissolved minerals such as calcium carbonate or bicarbonates. When alkaline irrigation water is used on soils, it can lead to soil alkalinity and increased soil pH levels over time. This effect is especially common in dry and semi-dry regions where water sources often come from limestone aquifers or contain high levels of dissolved carbonates (Benadela et al. 2022).

6.2.2 Appropriate Irrigation Practices

Appropriate irrigation practices are crucial for managing soil pH and minimizing the potential impacts of alkaline irrigation water. In the following sections, we will look in-depth at irrigation practices and their effect on soil pH.

6.2.2.1 Leaching

Leaching uses excess water to flush out salts and alkaline compounds from the root zone, preventing them from building up in the soil. During leaching, soluble salts and alkaline minerals are carried downward and removed from the root zone, which helps maintain optimal soil pH levels. This process is especially important in saline or sodic soils, where excessive salt accumulation can cause soil alkalinity and pH imbalances (Osman 2018).

6.2.2.2 Water pH adjustment

Adjusting the pH of irrigation water on a large scale is feasible and has been used in various agricultural practices, especially in regions with high water alkalinity or soils prone to becoming overly alkaline. By using acidifying agents such as sulfuric acid or citric acid in irrigation water, alkaline compounds can be neutralized, thus reducing their impact on soil pH when applied to the field (Neupane and Guo 2019; Rakibuzzaman et al. 2024). Precision water management systems, which include pH adjustment, are increasingly being adopted to improve water use efficiency and prevent soil degradation in large-scale farming operations (Neupane and Guo 2019; Rakibuzzaman et al. 2024).

6.2.2.3 Selection of Water Source

When possible, choosing irrigation water sources with lower alkalinity and mineral content can help reduce the risk of soil pH increase. Assessing water quality parameters such as pH, electrical conductivity (EC), and bicarbonate concentrations before irrigation can provide valuable information for water management decisions and help prevent potential soil pH problems (Rakibuzzaman et al. 2024).

6.3 Integration with Soil Management Practices

Combining effective irrigation management with soil management practices is crucial for achieving optimal soil pH levels and enhancing crop productivity. Soil testing and monitoring can help evaluate soil pH status and guide irrigation scheduling and water management decisions. In addition, soil amendments such as gypsum or elemental sulfur can help reduce soil alkalinity and maintain soil pH within the desired range. Moreover, pH-adjusting fertilizers, including controlled-release fertilizers (CRFs) and pH-balanced fertilizers, provide innovative solutions for managing soil pH while supplying essential nutrients to crops. These fertilizers are designed to release nutrients slowly and steadily over time, which helps maintain optimal soil pH levels and nutrient availability. The controlled release of nutrients aligns more closely with the plant's uptake needs, reducing nutrient losses and minimizing environmental impacts. This is particularly beneficial in managing soil pH as it prevents sudden changes in pH levels that could negatively impact soil health and crop productivity (Babadi et al. 2021; Li and Li 2024).

6.3.1 Controlled-release fertilizers

Controlled-release fertilizers (CRF) such as polymer-coated urea, sulfur-coated urea, polymer-sulfur-coated urea (PSCU), urea-formaldehyde (UF), isobutylidene diurea (IBDU), biochar-based coated fertilizers, and starch-based coated fertilizers are formulated with coated or encapsulated nutrient granules. These granules release nutrients slowly and continuously over an extended period. The release rate of nutrients from CRFs is controlled by factors such as temperature, moisture, and microbial activity in the soil. By providing a steady supply of nutrients to crops over time, CRFs help optimize nutrient uptake efficiency and reduce nutrient losses through leaching or volatilization. Additionally, the gradual release of nutrients from CRFs minimizes the risk of rapid pH changes in the soil, promoting more stable soil pH conditions conducive to optimal crop growth (Greenhouse Grower 2024).

6.3.2 pH-balanced fertilizers

pH-balanced fertilizers are specially formulated to provide essential nutrients without significantly altering soil pH levels. For example, calcium nitrate supplies calcium and nitrogen while maintaining a neutral to slightly alkaline pH, and potassium nitrate offers potassium and nitrogen without impacting soil acidity. Another pH-neutral option is magnesium sulfate, or Epsom salt, which provides magnesium and sulfur. Monoammonium phosphate (MAP) is frequently used for its balanced pH effect, making it ideal for crops with moderate pH requirements. While not a traditional fertilizer, gypsum adds calcium and sulfur without altering soil pH, making it useful for neutralizing excess sodium in soils. These pH-balanced fertilizers are suitable for sensitive crops and soils, helping to maintain optimal growing conditions (Warner et al. 2023).

These fertilizers typically contain buffering agents or additives that help stabilize soil pH and prevent pH fluctuations caused by nutrient applications. By balancing nutrient delivery with pH management, these fertilizers ensure that crops receive adequate nutrition while promoting soil health and fertility (Rahmat et al. 2023). Additionally, pH-balanced fertilizers are compatible with various soil types and cropping systems, providing flexibility and convenience for farmers in managing soil pH. Some of the most common benefits of using these fertilizers are given in the subsequent section of this article.

6.3.2.1 Optimized nutrient availability

Utilizing pH-adjusting fertilizers can help ensure that crops receive a consistent and balanced supply of nutrients, thus optimizing nutrient uptake and utilization. This is particularly crucial as soil pH significantly affects the availability of essential nutrients such as nitrogen, phosphorus, and potassium. Maintaining an optimal pH range enables plants to more effectively absorb these nutrients, leading to healthier growth and higher yields (Miller 2021).

6.3.2.2 Stable soil pH

pH-adjusting fertilizers help to maintain stable soil pH levels by incorporating pH-buffering agents and releasing nutrients gradually. This reduces the risk of pH imbalances, which can have a negative impact on crop productivity and soil health. The stability in soil pH provided by these fertilizers is crucial for sustaining long-term soil fertility and avoiding the problems associated with rapid pH changes, such as nutrient lock-up or toxicity (Potash Development Association 2021).

6.3.2.3 Reduced environmental impact

The controlled-release fertilizers (CRFs) in pH-adjusting formulations help minimize nutrient leaching and runoff, significantly contributing to water pollution. By slowly releasing nutrients, these fertilizers reduce the potential for nitrogen and phosphorus to enter water bodies, promoting environmental sustainability and protecting aquatic ecosystems (Oshunsanya 2019).

6.4 Technological innovations

6.4.1 Soil sensors and monitoring systems

Continuous monitoring of soil pH using sensors and monitoring systems provides real-time data on pH levels. This enables timely interventions to adjust pH as needed (Narayana et al. 2024), ensuring optimal crop growing conditions and facilitating data-driven decision-making in soil management.

6.4.2 Remote sensing and GIS technologies

6.4.2.1 Satellite imagery

Remote sensing technologies offer valuable insights into soil characteristics, including pH levels, across extensive agricultural landscapes. Satellite imagery can delineate spatial variations in soil pH, enabling targeted management interventions.

6.4.2.2 GIS mapping

Geographic Information Systems (GIS) allow for integrating soil pH data with other spatial information, including topography, land use, and weather patterns. This integration helps identify the factors that influence soil pH variability and enables the development of customized management strategies

6.5 Smart farming solutions

6.5.1 IoT and cloud computing

Integrating IoT and cloud computing in agriculture has transformed traditional farming methods by enabling real-time monitoring, data-driven decision-making, and automation. IoT devices such as sensors and drones continuously monitor soil moisture, temperature, humidity, and crop health. This data is then transmitted to cloud-based platforms, processed and analyzed to provide actionable insights for optimizing resource use, such as water and fertilizers. For instance, smart irrigation systems can automatically adjust water levels based on real-time soil moisture data, reducing water wastage and ensuring crops receive the optimal amount of water (Friha et al. 2021; Randazzo et al. 2022).

In precision farming, IoT and cloud computing allow farmers to apply inputs like fertilizers and pesticides with pinpoint accuracy tailored to the needs of individual crops or specific field areas. This targeted approach minimizes input use and maximizes yield, contributing to more sustainable agricultural practices (Mohammed et al. 2021). Additionally, cloud computing facilitates the processing of large datasets from multiple sources, such as weather forecasts and satellite imagery, to provide farmers with recommendations on planting and harvesting times, helping them adapt to changing climatic conditions and mitigate risks associated with unpredictable weather (Hori et al. 2010; Thilakarathne et al. 2023).

Studies have shown the effectiveness of these technologies in improving operational efficiency and productivity in agriculture. Friha et al. (2021) reviewed various IoT-based applications, including smart water management and disease management, and highlighted the potential of cloud and fog computing for real-time data processing. Similarly, Randazzo et al. (2022) explored the architecture of IoT-enabled smart agriculture, identifying opportunities for integrating big data and cloud computing to enhance agricultural sustainability. These advancements pave the way for more efficient, resilient, and sustainable farming practices (Friha et al. 2021; Randazzo et al. 2022; Thilakarathne et al. 2023).

6.5.2 Machine learning and AI

Machine learning (ML) and artificial intelligence (AI) are increasingly used in agriculture to enhance productivity, optimize resource utilization, and promote sustainable farming practices. These technologies are applied in various areas, including crop management, soil health monitoring, and predictive analytics for weather and pest control. For example, ML algorithms analyze data from sensors and drones to monitor crop health, detect diseases, and assess soil conditions in real-time. This allows farmers to make well-informed decisions regarding irrigation, fertilization, and pest management, ultimately leading to improved yields and reduced environmental impact (Benos et al. 2021). AI and ML are also employed in automated machinery and robotics in agriculture. Autonomous tractors and harvesters equipped with AI can perform tasks such as planting, weeding, and harvesting with minimal human intervention. This reduces labour costs and ensures precision in farming activities, resulting in higher efficiency and productivity (Jha et al. 2018). Additionally, AI-driven platforms are being developed for supply chain management to help predict market demands, optimize logistics, and reduce food wastage. These platforms use predictive analytics to anticipate supply and demand trends, enabling better planning and distribution of agricultural products (Hassan et al. 2021). These technologies hold great potential for transforming traditional farming into a more data-driven, precise, and sustainable system. The adoption of AI and ML in agriculture is expected to grow as new applications and technologies emerge, further enhancing agricultural productivity and sustainability (Pallathadka et al. 2023).

6.6 Advanced soil amendments

6.6.1 Nano- and microscale amendments

Nano- and microscale amendments, such as nanofertilizers and nanopesticides, offer significant agricultural productivity and sustainability advancements. These amendments are designed to improve nutrient use efficiency, reduce environmental impacts, enhance plant resilience to stress conditions, and help maintain soil pH. Nanofertilizers are engineered to deliver nutrients more effectively to plants by utilizing nanoparticles that provide a larger surface area and improved solubility than traditional fertilizers. This leads to more efficient nutrient uptake and reduced losses due to leaching or volatilization, indirectly affecting soil pH. These nanomaterials ensure a controlled release of active ingredients, enhancing their effectiveness while lowering environmental risks associated with pH change (Victoria et al. 2023). The application of these nano- and microscale technologies is not limited to nutrient delivery and pest control. They also play a role in soil and water remediation, helping to remove contaminants and improve soil health (Behera et al. 2022). These innovative solutions are part of a broader move towards sustainable agriculture, where precision and efficiency are prioritized to meet the growing global food demand without compromising environmental integrity (Akhtar et al. 2022).

6.6.2 Biochar and soil conditioners

Biochar is a carbon-rich product made from the pyrolysis of organic materials like agricultural waste and biomass. It is increasingly recognized as an effective soil conditioner in sustainable agriculture. Its application offers multiple benefits, including improved soil fertility, enhanced nutrient retention, increased water-holding capacity, long-term carbon sequestration, and pH maintenance. Biochar's porous structure allows it to retain nutrients and water, making it more available to plants and reducing nutrient leaching. This can significantly improve crop yields, especially in degraded soils or areas with poor soil fertility (Alotaibi and Schoenau 2019). Additionally, biochar's ability to act as a habitat for beneficial soil microbes promotes a healthy soil ecosystem, indirectly affecting soil pH, which enhances the soil's capacity to support plant growth and resist diseases. Moreover, biochar is highly stable and potentially sequesters carbon. However, the effectiveness of biochar can vary based on factors such as the type of feedstock used, the pyrolysis process, and the specific soil and climatic conditions. While biochar generally improves soil properties and crop yields, some studies have reported inconsistent results in different environmental settings, emphasizing more region-specific research and long-term field trials to understand better its impacts (Galinato et al. 2011; Pandit et al. 2018). In addition to biochar, other soil conditioners such as gypsum, lime, and organic amendments enhance soil structure, pH balance, and nutrient availability. Integrating biochar with these conditioners can offer synergistic benefits, improving soil health and agricultural productivity (Anawar et al. 2015).

6.6.3 Biological approaches

Microbial inoculants, such as specific bacteria and fungi, can help regulate soil pH by enhancing organic matter decomposition and nutrient cycling. These biological approaches offer sustainable solutions for long-term soil health (Johnston and Goulding 1990).

Conclusion and Future Prospects

It is crucial to manage soil pH for sustainable agriculture and ecosystem health. Soil pH directly affects nutrient availability, microbial activity, and soil fertility, influencing crop growth and productivity. Farmers can maintain soil pH balance and fertility using traditional methods like liming, crop selection and rotation, and organic matter management. Modern technological innovations, such as precision agriculture technologies and biological approaches like microbial inoculants and plant-microbe interactions, offer efficient ways to manage soil pH at a finer spatial scale. Future research should focus on creating integrated approaches that combine these strategies to maximize soil resilience, productivity, and sustainability.

The biochar and soil conditioners study shows significant potential for enhancing soil health and sustainable agricultural practices. Biochar, a carbon-rich material produced through the pyrolysis of organic waste, has shown promise in improving soil properties such as fertility, water retention, and nutrient availability. Future studies should focus on large-scale, long-term field trials to better understand the interactions between biochar, soil, and crops over time. It is also important to explore the integration of biochar with other soil conditioners, such as compost and gypsum, to assess their synergistic effects on soil health and productivity. Furthermore, research should address biochar production's economic and environmental feasibility, considering cost, scalability, and potential carbon sequestration benefits. Understanding the role of biochar in mitigating climate change by capturing atmospheric carbon and reducing greenhouse gas emissions from agriculture is crucial for developing sustainable farming practices. Addressing these research gaps will contribute to formulating effective biochar-based strategies for improving soil management and ensuring long-term agricultural sustainability.

Conflict of Interest

Authors declared no conflict of interest with each other.

Ethical Clearance

It is certified that no animal or human model was used during the study, so there is no need for any ethical clearance.

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