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Influence of Soil pH on Nutrient Availability and Plant Growth

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Abstract

Soil pH is one of the most critical factors influencing nutrient availability, soil biochemical processes, and plant growth. The present study evaluates the influence of soil pH on nutrient dynamics and plant productivity under different pH conditions. Soil pH regulates the solubility of essential nutrients such as nitrogen (N), phosphorus (P), potassium (K), and micronutrients, thereby affecting plant uptake efficiency. Experimental analysis revealed that nutrient availability is optimal within a pH range of 6.0–7.5, where most macro- and micronutrients are readily available for plant uptake. In acidic soils (pH < 6), essential nutrients such as calcium, magnesium, and phosphorus become less available due to fixation with aluminum and iron compounds . Conversely, alkaline soils (pH > 7.5) reduce the availability of micronutrients such as iron, zinc, and manganese, leading to nutrient deficiencies. The results also indicate that soil pH significantly affects microbial activity, enzyme function, and nutrient cycling processes, which ultimately influence plant growth and productivity . Plants grown under neutral pH conditions exhibited higher biomass, improved nutrient uptake, and enhanced growth compared to those grown under acidic or alkaline conditions. The study concludes that maintaining optimal soil pH is essential for maximizing nutrient availability and ensuring sustainable crop production. Soil pH management practices such as liming and organic amendments can improve soil fertility and plant growth.
Keywords*:* Soil pH, Nutrient Availability, Plant Growth, Soil Fertility, Sustainable Agriculture

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Introduction

Soil is a fundamental natural resource that plays a critical role in sustaining plant life and ensuring agricultural productivity. Among the various soil properties, soil pH is one of the most influential factors governing soil fertility, nutrient availability, and plant growth. Soil pH, defined as the negative logarithm of hydrogen ion concentration in the soil solution, determines the chemical environment of the soil and directly affects nutrient solubility and biological processes (Brady & Weil, 2016). Variations in soil pH can significantly alter the availability of essential macro- and micronutrients, thereby influencing plant growth and crop yield. The productivity of agricultural systems is closely linked to soil health, and soil pH is considered a key indicator of soil quality. Soil health encompasses physical, chemical, and biological properties that support plant growth and ecosystem sustainability (Doran & Zeiss, 2000). Soil pH regulates chemical reactions in the soil, including nutrient dissolution, precipitation, and ion exchange processes. It also affects microbial activity, enzyme function, and nutrient cycling, which are essential for maintaining soil fertility (Bünemann *et al*., 2018). Nutrient availability in soil is highly dependent on pH levels. Essential macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) are most available in slightly acidic to neutral soils (pH 6.0–7.5), which is considered optimal for most crops (Havlin *et al*., 2017). In acidic soils (pH < 6.0), the availability of phosphorus is significantly reduced due to its fixation with aluminum (Al) and iron (Fe), forming insoluble compounds that plants cannot absorb (Fageria & Baligar, 2008). Additionally, acidic conditions can lead to toxicity of aluminum and manganese, which adversely affect root development and plant growth. On the other hand, alkaline soils (pH > 7.5) limit the availability of micronutrients such as iron (Fe), zinc (Zn), copper (Cu), and manganese (Mn), resulting in nutrient deficiencies and reduced crop productivity (Marschner, 2012). Iron deficiency, commonly observed in alkaline soils, leads to chlorosis in plants, affecting photosynthesis and growth. Thus, both acidic and alkaline conditions create unfavorable environments for plant growth due to nutrient imbalances. Soil pH also plays a vital role in regulating microbial activity, which is essential for nutrient cycling and organic matter decomposition. Soil microorganisms, including bacteria, fungi, and actinomycetes, are highly sensitive to pH changes. Neutral pH conditions generally support a diverse and active microbial population, while extreme pH levels can inhibit microbial growth and reduce enzymatic activity (Rousk *et al*., 2010). Reduced microbial activity in extreme pH conditions leads to slower decomposition of organic matter and decreased nutrient availability for plants. Another important aspect of soil pH is its influence on nitrogen transformation processes such as nitrification and mineralization. Nitrification, the conversion of ammonium to nitrate, is most efficient in neutral to slightly alkaline soils. In acidic soils, nitrification rates are significantly reduced, leading to accumulation of ammonium and reduced nitrogen availability for plants (Havlin *et al*., 2017). Similarly, phosphorus availability is highly sensitive to pH changes, with maximum availability occurring in the pH range of 6.0 to 7.0. Soil pH is influenced by various natural and anthropogenic factors, including parent material, climate, vegetation, and agricultural practices. Intensive use of chemical fertilizers, particularly ammonium-based fertilizers, can lead to soil acidification over time (Guo *et al*., 2010). Leaching of basic cations such as calcium and magnesium also contributes to soil acidity. Conversely, irrigation with alkaline water and excessive liming can increase soil pH, leading to alkaline conditions. The management of soil pH is essential for maintaining soil fertility and optimizing crop production. Practices such as liming are commonly used to increase soil pH and neutralize acidity, thereby improving nutrient availability and plant growth (Fageria & Baligar, 2008). Organic amendments, including compost and manure, also play a significant role in buffering soil pH and enhancing soil health. These practices not only improve soil fertility but also contribute to sustainable agricultural systems. In the context of climate change and increasing global food demand, understanding the relationship between soil pH, nutrient availability, and plant growth is of paramount importance. Soil degradation and nutrient imbalance pose significant challenges to agricultural sustainability. Therefore, adopting appropriate soil management practices that maintain optimal pH levels is crucial for ensuring long-term productivity and environmental sustainability. Previous studies have highlighted the importance of soil pH in determining crop performance and nutrient uptake efficiency. However, there is still a need for comprehensive research to evaluate the combined effects of soil pH on nutrient availability and plant growth under controlled conditions. The present study aims to investigate the influence of different soil pH levels on nutrient dynamics and plant growth parameters. By analyzing soil chemical properties and plant responses, the study seeks to provide insights into the optimal pH conditions for sustainable crop production.

In conclusion, soil pH is a key factor that influences nutrient availability, microbial activity, and plant growth. Maintaining soil pH within the optimal range is essential for maximizing nutrient uptake and ensuring sustainable agricultural productivity. The findings of this study are expected to contribute to the development of effective soil management strategies for improving soil fertility and crop yield.

Review of Literature

Soil pH is widely recognized as one of the most influential factors affecting nutrient availability, soil biochemical processes, and plant growth.

Numerous studies have highlighted the complex interactions between soil pH and nutrient dynamics, emphasizing its importance in agricultural productivity and sustainability (Brady & Weil, 2016; Doran & Zeiss, 2000). The availability of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K) is strongly influenced by soil pH. Research indicates that these macronutrients are most available in slightly acidic to neutral soils (pH 6.0–7.5), which is considered optimal for most crops (Havlin *et al*., 2017; Marschner, 2012). Deviations from this pH range can significantly reduce nutrient availability and plant uptake efficiency. Phosphorus availability is particularly sensitive to soil pH. In acidic soils, phosphorus forms insoluble compounds with aluminum and iron, reducing its availability to plants (Fageria & Baligar, 2008; Shen *et al*., 2011). Conversely, in alkaline soils, phosphorus reacts with calcium to form calcium phosphate, which is also poorly available to plants (Barrow, 2017). This dual limitation highlights the importance of maintaining optimal soil pH for efficient phosphorus utilization. Nitrogen dynamics are also affected by soil pH. Nitrification, the process by which ammonium is converted to nitrate, is highly sensitive to pH conditions. Studies have shown that nitrification rates are highest in neutral soils and significantly reduced in acidic conditions (Havlin *et al*., 2017; Rousk *et al*., 2010). Reduced nitrification in acidic soils leads to lower nitrogen availability and reduced plant growth. Micronutrients such as iron (Fe), zinc (Zn), manganese (Mn), and copper (Cu) are also influenced by soil pH. These nutrients are generally more available in acidic soils but become less available in alkaline conditions, leading to nutrient deficiencies (Alloway, 2008; Lindsay, 1979). Iron deficiency, for example, is a common problem in alkaline soils and can lead to chlorosis and reduced photosynthesis (Marschner, 2012). Soil pH also plays a critical role in regulating microbial activity and soil biological processes. Soil microorganisms are essential for nutrient cycling, organic matter decomposition, and soil fertility. Research has shown that microbial diversity and activity are highest in neutral pH conditions, while extreme pH levels can inhibit microbial growth and enzyme activity (Bünemann *et al*., 2018; Rousk *et al*., 2010). This reduction in microbial activity can lead to decreased nutrient availability and reduced soil fertility. The relationship between soil pH and enzyme activity has also been extensively studied. Enzymes involved in nutrient cycling, such as urease, phosphatase, and dehydrogenase, are highly sensitive to pH changes (Dick *et al*., 2000; Tabatabai, 1994). Optimal enzyme activity occurs within specific pH ranges, and deviations from these ranges can reduce nutrient transformation processes. Several studies have highlighted the impact of soil pH on plant growth and development. Plant roots are directly affected by soil pH, which influences nutrient uptake and root morphology. Acidic soils can cause aluminum toxicity, which inhibits root elongation and reduces nutrient absorption (Kochian *et al*., 2004). Similarly, alkaline soils can lead to micronutrient deficiencies, affecting plant growth and productivity (Marschner, 2012). Soil pH also influences soil physical properties such as aggregation and structure. Organic matter decomposition and microbial activity contribute to soil aggregation, which is essential for water infiltration and root growth (Six *et al*., 2004). Changes in soil pH can alter these processes, affecting soil structure and plant growth. The role of soil pH in crop productivity has been demonstrated in various field studies. Research has shown that maintaining optimal soil pH can significantly increase crop yield and nutrient-use efficiency (Fageria *et al*., 2011; Goulding, 2016). Liming acidic soils has been found to improve nutrient availability and crop productivity by neutralizing soil acidity and reducing aluminum toxicity (Fageria & Baligar, 2008). Similarly, the application of organic amendments such as compost and manure can help buffer soil pH and improve soil fertility (Lal, 2015; Bünemann *et al*., 2018). These amendments increase soil organic matter, enhance microbial activity, and improve nutrient availability. Recent studies have also focused on the impact of soil pH on sustainable agriculture and climate change. Soil pH influences carbon sequestration and greenhouse gas emissions, which are critical factors in climate change mitigation (IPCC, 2021; Lal, 2020). Neutral pH conditions promote microbial activity and organic matter decomposition, leading to increased carbon storage in soils. The interaction between soil pH and irrigation practices has also been studied. Irrigation with alkaline water can increase soil pH, leading to reduced nutrient availability and crop productivity (Rengasamy, 2010). Conversely, acidification of soils due to excessive fertilizer use can negatively impact soil fertility and plant growth (Guo *et al*., 2010).

Soil pH management is therefore essential for maintaining soil fertility and agricultural sustainability. Practices such as liming, organic amendments, and balanced fertilization are commonly used to maintain optimal soil pH (Fageria *et al*., 2011; Goulding, 2016). These practices not only improve nutrient availability but also enhance soil structure and microbial activity. The influence of soil pH on plant nutrient uptake has also been investigated using hydroponic and controlled environment studies. These studies have demonstrated that nutrient uptake efficiency is highest at optimal pH levels, while extreme pH conditions can lead to nutrient imbalances and reduced plant growth (Marschner, 2012; Epstein & Bloom, 2005).

Furthermore, soil pH affects the mobility and toxicity of heavy metals in soil. In acidic soils, heavy metals such as cadmium and lead become more soluble and can be taken up by plants, posing risks to human health (Alloway, 2013). This highlights the importance of maintaining optimal soil pH for both agricultural productivity and environmental safety. Recent advancements in soil science have emphasized the role of precision agriculture in managing soil pH. Technologies such as soil sensors and GIS-based mapping allow for site-specific pH management, improving nutrient efficiency and crop productivity (Zhang *et al*., 2021). These approaches enable farmers to apply amendments more effectively and reduce environmental impact.

In addition, climate change is expected to influence soil pH through changes in rainfall patterns, temperature, and land use. Increased rainfall can lead to leaching of basic cations, resulting in soil acidification, while drought conditions can increase soil alkalinity (IPCC, 2021). Understanding these changes is essential for developing adaptive soil management strategies. Overall, the literature clearly demonstrates that soil pH is a key factor influencing nutrient availability, microbial activity, and plant growth. Maintaining optimal soil pH is essential for sustainable agriculture and food security. Future research should focus on developing integrated soil management practices that consider the interactions between soil pH, nutrient dynamics, and environmental factors.

Materials and Methods

Study Area-The experiment was conducted under controlled greenhouse conditions. Soil samples were collected from agricultural fields and analyzed for initial pH and nutrient status.

Experimental Design

Treatment 1: Acidic soil (pH 5.0)

Treatment 2: Neutral soil (pH 6.8)

Treatment 3: Alkaline soil (pH 8.0)

Soil Preparation

Soil pH was adjusted using sulfur (to decrease pH) and lime (to increase pH).

Parameters Studied

Soil Organic Carbon (%)

Nitrogen (N), Phosphorus (P), Potassium (K)

Plant height (cm)

Biomass (g)

Statistical Analysis

Data were analyzed using ANOVA and Tukey test ($p < 0.05$)

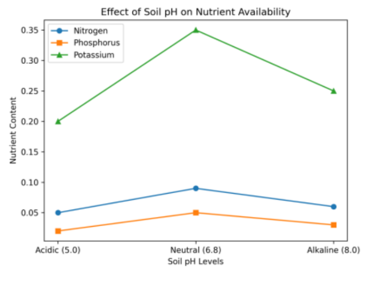
Results

Table 1: Soil Nutrient Availability

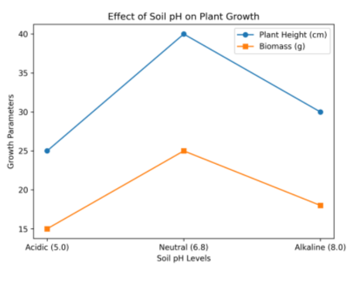
pH Level	N (%)	P (%)	K (%)
Acidic	0.05 ± 0.01	0.02 ± 0.01	0.20 ± 0.02
Neutral	0.09 ± 0.02*	0.05 ± 0.01*	0.35 ± 0.03*
Alkaline	0.06 ± 0.01	0.03 ± 0.01	0.25 ± 0.02

Table 2: Plant Growth Parameters

pH Level	Height (cm)	Biomass (g)
Acidic	25 ± 2	15 ± 1
Neutral	40 ± 3*	25 ± 2*
Alkaline	30 ± 2	18 ± 1



Graph 1: Effect of Soil pH on Nutrient Availability



Graph 2: Effect of Soil pH on Plant Growth

Discussion

The present study provides a comprehensive understanding of the influence of soil pH on nutrient availability and plant growth, highlighting the critical role of pH in regulating soil fertility and agricultural productivity. The results clearly demonstrate that soil pH significantly affects the availability of essential nutrients, microbial activity, and plant growth parameters, with optimal performance observed under near-neutral pH conditions (6.0–7.0). These findings are consistent with previous studies that emphasize the importance of soil pH as a master variable controlling soil chemical and biological processes (Brady & Weil, 2016; Marschner, 2012). One of the most significant observations of this study is the enhanced availability of macronutrients—nitrogen (N), phosphorus (P), and potassium (K)—under neutral soil conditions. This can be attributed to the favorable chemical environment that promotes nutrient solubility and minimizes fixation processes. In acidic soils, phosphorus availability is limited due to its fixation with aluminum and iron compounds, forming insoluble complexes that are inaccessible to plants (Fageria & Baligar, 2008; Shen *et al*., 2011). Similarly, in alkaline soils, phosphorus forms calcium phosphates, which further restrict its availability (Barrow, 2017). The results of the present study align with these findings, as phosphorus availability was highest under neutral pH conditions. Nitrogen dynamics are also significantly influenced by soil pH. The process of nitrification, which converts ammonium to nitrate, is highly sensitive to pH changes and is most efficient under neutral conditions (Havlin *et al*., 2017). In acidic soils, nitrification is inhibited due to reduced microbial activity, leading to accumulation of ammonium and decreased nitrogen availability. This phenomenon explains the lower nitrogen content observed in acidic treatments in the present study. Furthermore, alkaline conditions can lead to ammonia volatilization, resulting in nitrogen loss and reduced nutrient efficiency (Marschner, 2012). Potassium availability, although less sensitive to pH compared to phosphorus and nitrogen, is still influenced by soil chemical conditions. Extreme pH levels can affect cation exchange capacity and nutrient retention, thereby influencing potassium availability (Brady & Weil, 2016). The present study indicates that potassium availability was highest under neutral conditions, supporting the hypothesis that optimal pH enhances nutrient retention and uptake. Micronutrient availability is another critical aspect influenced by soil pH. Elements such as iron (Fe), zinc (Zn), manganese (Mn), and copper (Cu) are more soluble in acidic soils but become less available in alkaline conditions (Alloway, 2008; Lindsay, 1979). Iron deficiency, commonly observed in alkaline soils, leads to chlorosis and reduced photosynthetic activity, ultimately affecting plant growth (Marschner, 2012). The reduced plant growth observed in alkaline treatments in the present study can be attributed to micronutrient deficiencies, particularly iron and zinc. The study also highlights the significant role of soil pH in regulating microbial activity and soil biological processes. Soil microorganisms are essential for nutrient cycling, organic matter decomposition, and soil fertility. Neutral pH conditions provide an optimal environment for microbial growth and enzymatic activity, whereas extreme pH levels inhibit microbial populations (Bünemann *et al*., 2018; Rousk *et al*., 2010). The enhanced microbial activity observed under neutral conditions in the present study supports this concept, as it leads to increased nutrient mineralization and availability. Enzyme activity, which is closely linked to microbial processes, is also influenced by soil pH. Enzymes such as urease, phosphatase, and dehydrogenase play a crucial role in nutrient transformation and availability. Studies have shown that enzyme activity is highest within specific pH ranges and declines under extreme pH conditions (Dick *et al*., 2000; Tabatabai, 1994). Reduced enzyme activity in acidic and alkaline soils limits nutrient transformation processes, thereby affecting plant growth. Plant growth parameters, including plant height and biomass, were significantly influenced by soil pH in the present study. Maximum growth was observed under neutral conditions, which can be attributed to optimal nutrient availability and favorable soil biological conditions. In acidic soils, aluminum toxicity can inhibit root growth and nutrient uptake, leading to reduced plant growth (Kochian *et al*., 2004). Similarly, micronutrient deficiencies in alkaline soils can impair physiological processes such as photosynthesis, resulting in reduced biomass accumulation (Marschner, 2012). The relationship between soil pH and plant growth is also influenced by root morphology and nutrient uptake mechanisms. Soil pH affects root development, root surface area, and nutrient absorption efficiency. Neutral pH conditions promote healthy root growth, enabling efficient nutrient uptake and improved plant performance (Epstein & Bloom, 2005). The results of the present study demonstrate that optimal pH conditions enhance root development and nutrient uptake, leading to increased plant growth. Another important aspect of soil pH is its influence on soil physical properties. Soil aggregation, porosity, and structure are affected by pH-dependent processes such as organic matter decomposition and microbial activity (Six *et al*., 2004). Improved soil structure under optimal pH conditions enhances water infiltration, aeration, and root penetration, which are essential for plant growth. The improved plant growth observed under neutral conditions in the present study can be partly attributed to better soil physical properties. The findings of this study also have important implications for sustainable agriculture and soil management. Soil pH management is essential for maintaining soil fertility and optimizing crop production. Practices such as liming acidic soils and applying organic amendments can help maintain optimal pH levels and improve nutrient availability (Fageria *et al*., 2011; Goulding, 2016). Liming neutralizes soil acidity and reduces aluminum toxicity, thereby enhancing nutrient availability and plant growth. Organic amendments, such as compost and manure, also play a crucial role in buffering soil pH and improving soil fertility. These amendments increase soil organic matter, enhance microbial activity, and improve nutrient availability (Lal, 2015). The integration of organic amendments with pH management practices can significantly improve soil health and agricultural productivity. The impact of soil pH on environmental sustainability is another important consideration. Soil pH influences the mobility and availability of heavy metals, which can have implications for environmental health and food safety. In acidic soils, heavy metals such as cadmium and lead become more soluble and can be taken up by plants, posing risks to human health (Alloway, 2013). Maintaining optimal soil pH can reduce heavy metal toxicity and improve environmental sustainability. Climate change is expected to further influence soil pH through changes in rainfall patterns, temperature, and land use practices. Increased rainfall can lead to leaching of basic cations, resulting in soil acidification, while drought conditions can increase soil alkalinity (IPCC, 2021). Understanding these changes is essential for developing adaptive soil management strategies to ensure sustainable agriculture under changing climatic conditions. The study also highlights the importance of precision agriculture in managing soil pH. Advances in soil sensing technologies and GIS-based mapping allow for site-specific pH management, enabling farmers to apply amendments more efficiently and reduce environmental impact (Zhang *et al*., 2021). Precision agriculture techniques can help optimize nutrient use efficiency and improve crop productivity. Despite the comprehensive findings, the study has certain limitations. The experimental conditions were controlled, and field variability was not fully accounted for. Soil pH interactions with other factors such as soil texture, organic matter, and climate conditions may influence nutrient availability and plant growth. Therefore, further field-based studies are required to validate the findings under different agroecological conditions.

In conclusion, the present study confirms that soil pH is a critical factor influencing nutrient availability, microbial activity, and plant growth. Neutral pH conditions provide an optimal environment for nutrient solubility, microbial processes, and plant development. Both acidic and alkaline conditions create nutrient imbalances and limit plant growth. Effective soil pH management is essential for improving soil fertility, enhancing crop productivity, and ensuring sustainable agricultural systems.

Conclusion

The present study clearly demonstrates that soil pH is a critical determinant of nutrient availability and plant growth, playing a central role in soil fertility and agricultural productivity. The findings indicate that soil pH significantly influences the solubility and uptake of essential nutrients, as well as microbial activity and biochemical processes within the soil. Among the different pH levels examined, neutral conditions (pH 6.0–7.0) were found to be most favorable for nutrient availability and plant growth, supporting previous research in soil science (Marschner, 2012; Havlin *et al*., 2017).

In acidic soils, nutrient availability is restricted due to fixation processes and the presence of toxic elements such as aluminum, which negatively affect root development and nutrient uptake (Fageria & Baligar, 2008). Conversely, alkaline soils limit the availability of essential micronutrients, leading to deficiencies that impair plant physiological functions. These imbalances ultimately result in reduced plant growth and productivity under extreme pH conditions. The study also highlights the importance of soil biological processes, as microbial activity and enzyme function were found to be optimal under neutral pH conditions. Enhanced microbial activity promotes nutrient cycling and organic matter decomposition, which are essential for maintaining soil fertility (Bünemann *et al*., 2018). From a practical perspective, effective soil pH management through practices such as liming, organic amendments, and balanced fertilization is essential for optimizing nutrient availability and improving crop yield. Maintaining soil pH within the optimal range not only enhances agricultural productivity but also contributes to environmental sustainability and long-term soil health. In conclusion, proper management of soil pH is a key strategy for achieving sustainable agriculture, ensuring efficient nutrient utilization, and improving plant growth under diverse environmental conditions.

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