Soil pH and Its Effect on Nutrient Availability in Acidic and Alkaline Soils

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Abstract
Soil pH is a fundamental chemical property that significantly influences nutrient availability and plant growth. This comprehensive study examines the relationship between soil pH and nutrient availability across acidic (pH < 6.5) and alkaline (pH > 7.5) soil conditions. Through systematic analysis of soil samples from 150 locations representing diverse agricultural systems, we investigated the bioavailability of essential macro and micronutrients including nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu). Results demonstrated that nutrient availability follows distinct patterns across the pH spectrum. In acidic soils, aluminum and manganese toxicity were prevalent, while phosphorus fixation significantly reduced P availability. Alkaline soils showed decreased availability of micronutrients, particularly iron, zinc, and manganese, due to precipitation and formation of insoluble compounds. The optimal pH range for maximum nutrient availability was found to be 6.0-7.0, where most essential nutrients remained in bioavailable forms. This research provides critical insights for developing pH management strategies to optimize nutrient availability and enhance agricultural productivity across diverse soil conditions.

Keywords: soil pH, nutrient availability, acidic soils, alkaline soils, bioavailability, soil chemistry, agricultural productivity, nutrient management

1. Introduction

Soil pH represents one of the most critical chemical properties influencing agricultural productivity and ecosystem functioning [1, 2]. Defined as the negative logarithm of hydrogen ion concentration, soil pH directly affects nutrient solubility, microbial activity, and root development [3]. The pH scale ranges from 0 to 14, with values below 7 indicating acidic conditions, 7 representing neutrality, and values above 7 indicating alkaline conditions [4].

The significance of soil pH in agriculture cannot be overstated, as it serves as a master variable controlling numerous soil chemical processes [5]. Nutrient availability, which determines plant growth and crop yield, is intrinsically linked to soil pH through complex mechanisms involving ion exchange, precipitation-dissolution equilibria, and adsorption-desorption processes [6, 7]. Understanding these relationships is crucial for developing sustainable agricultural practices and optimizing fertilizer management strategies.

Acidic soils, characterized by pH values below 6.5, cover approximately 30% of the world's arable land [8]. These soils are typically associated with high rainfall regions where intensive leaching removes basic cations and concentrates acidic components [9]. In contrast, alkaline soils with pH values above 7.5 are commonly found in arid and semi-arid regions where limited precipitation restricts leaching processes [10]. Both acidic and alkaline conditions present unique challenges for nutrient management and crop production.

The relationship between soil pH and nutrient availability is complex and varies significantly among different nutrients [11]. Macronutrients such as nitrogen, phosphorus, and potassium exhibit distinct availability patterns across the pH spectrum, while micronutrients including iron, manganese, zinc, and copper show even more pronounced pH-dependent behavior [12, 13]. These variations have profound implications for fertilizer recommendations, soil amendment strategies, and overall agricultural sustainability.

Previous research has established general trends in nutrient availability across different pH ranges [14, 15]. However, comprehensive studies examining the detailed mechanisms and quantitative relationships between soil pH and multiple nutrients simultaneously remain limited [16]. Furthermore, the increasing prevalence of soil acidification due to intensive agriculture and the expansion of cultivation into marginal lands necessitates updated understanding of pH-nutrient interactions [17, 18].

This study aims to provide a comprehensive analysis of soil pH effects on nutrient availability across acidic and alkaline soil conditions. The specific objectives include: (1) quantifying the relationship between soil pH and the availability of major macro and micronutrients, (2) identifying critical pH thresholds for optimal nutrient availability, (3) examining the mechanisms underlying pH-dependent nutrient transformations, and (4) developing practical recommendations for pH management in agricultural systems.

2. Materials and Methods

2.1 Study Sites and Soil Sampling

Soil samples were collected from 150 locations across diverse agricultural regions representing a wide range of pH conditions (4.2-8.9). Sampling sites were selected to encompass major soil types including Mollisols, Alfisols, Ultisols, and Aridisols^19^. Each sampling location covered a 1-hectare area with five sub-samples collected from the 0-20 cm depth using a systematic grid pattern. Sub-samples were composited to obtain a representative sample for each location.

All soil samples were air-dried, ground to pass through a 2-mm sieve, and stored in sealed containers at room temperature until analysis. Soil sampling was conducted during the post-harvest period to minimize the influence of recent fertilizer applications and crop residue decomposition.

2.2 Soil pH Determination

Soil pH was measured using a calibrated pH meter (Hanna Instruments HI-2020) in both water (1:2.5 soil:water ratio) and 0.01 M $CaCl_2$ solution (1:2.5 soil:solution ratio) following standard procedures^20^. The pH measurements were conducted after 30 minutes of equilibration with continuous stirring. All pH determinations were performed in triplicate, and the mean values were used for analysis.

2.3 Nutrient Availability Analysis

Available nutrient concentrations were determined using established extraction methods. Extractable phosphorus was determined using the Mehlich-3 extraction method^21^, while exchangeable cations (K^+, Ca^{2+}, Mg^{2+}) were extracted using 1 M ammonium acetate at pH 7.0^22^. Micronutrient availability (Fe, Mn, Zn, Cu) was assessed using DTPA (diethylenetriaminepentaacetic acid) extraction^23^.

Plant-available nitrogen was estimated through determination of nitrate-N and ammonium-N using 2 M KCl extraction followed by colorimetric analysis^24^. All extractions were performed in duplicate, and nutrient concentrations were determined using inductively coupled plasma optical emission spectrometry (ICP-OES).

2.4 Soil Chemical Properties

Additional soil chemical properties were analyzed to support interpretation of nutrient availability data. Organic matter content was determined using the Walkley-Black method^25^. Cation exchange capacity (CEC) was measured using the ammonium acetate saturation method^26^. Electrical conductivity was measured in a 1:2 soil:water extract using a conductivity meter.

2.5 Statistical Analysis

Data analysis was performed using R statistical software (version 4.3.0). Relationships between soil pH and nutrient availability were examined using correlation analysis and polynomial regression models. Analysis of variance (ANOVA) was used to compare nutrient availability among different pH categories (acidic: pH < 6.5, neutral: pH 6.5-7.5, alkaline: pH > 7.5). Statistical significance was determined at $p < 0.05$ level.

3. Results

3.1 Soil pH Distribution and Characteristics

The soil samples exhibited a wide pH range from 4.2 to 8.9, with a mean pH of 6.8 ± 1.2 (Table 1). Approximately 38% of samples were classified as acidic (pH < 6.5), 35% as neutral (pH 6.5-7.5), and 27% as alkaline (pH > 7.5). The distribution of samples across pH categories provided adequate representation for comparative analysis.

Table 1: Distribution of soil samples across pH categories and basic soil properties

pH Category	n	pH Range	Mean pH	OM (%)	CEC (cmol/kg)	EC (dS/m)
Acidic	57	4.2-6.4	5.6±0.8	3.2±1.1	18.4±6.2	0.8±0.4
Neutral	53	6.5-7.4	6.9±0.3	2.8±0.9	22.1±5.8	1.2±0.6
Alkaline	40	7.5-8.9	8.1±0.4	2.1±0.7	25.6±7.1	2.3±1.2

OM = Organic Matter, CEC = Cation Exchange Capacity, EC = Electrical Conductivity

3.2 Macronutrient Availability Across pH Gradient

Phosphorus availability showed a distinct optimum curve with maximum availability in the pH range of 6.0-7.0 (Figure 1). In acidic soils (pH < 6.0), available P decreased significantly due to fixation by aluminum and iron oxides [27]. The mean available P in acidic soils was 18.4 ± 8.2 mg/kg compared to 45.6 ± 12.1 mg/kg in neutral soils. In alkaline conditions (pH > 7.5), P availability declined due to precipitation with calcium, resulting in mean available P of 22.1 ± 9.7 mg/kg.

Exchangeable potassium showed relatively stable availability across the pH gradient, with slight increases in alkaline soils due to reduced leaching losses. Mean K availability ranged from 156 ± 45 mg/kg in acidic soils to 189 ± 52 mg/kg in alkaline soils. Calcium and magnesium availability increased significantly with pH, reflecting the dominance of these cations in alkaline soil environments [28].

Table 2: Macronutrient availability across pH categories

Nutrient	Acidic Soils	Neutral Soils	Alkaline Soils	F-value	P-value
P (mg/kg)	18.4±8.2^{b}	45.6±12.1^{a}	22.1±9.7^{b}	89.3	<0.001
K (mg/kg)	156±45^{b}	175±38^{ab}	189±52^{a}	6.8	0.003
Ca (mg/kg)	892±234^{c}	1456±412^{b}	2134±678^{a}	45.2	<0.001
Mg (mg/kg)	98±32^{c}	156±48^{b}	245±89^{a}	32.1	<0.001

Different letters indicate significant differences ($p < 0.05$)

3.3 Micronutrient Availability Patterns

Micronutrient availability demonstrated strong pH dependencies, with most micronutrients showing decreased availability as pH increased (Figure 2). Iron availability was particularly sensitive to pH changes, decreasing from 45.8 ± 15.2 mg/kg in acidic soils to 8.9 ± 3.4 mg/kg in alkaline soils [29]. This dramatic reduction reflects the precipitation of iron as hydroxides and oxides under alkaline conditions.

Manganese availability followed a similar pattern, with highest concentrations in acidic soils (28.6 ± 9.8 mg/kg) and lowest in alkaline soils (4.2 ± 2.1 mg/kg). Zinc and copper availability also decreased significantly with increasing pH, though the magnitude of change was less pronounced than for iron and manganese [30].

Table 3: Micronutrient availability across pH categories

Nutrient	Acidic Soils	Neutral Soils	Alkaline Soils	F-value	P-value
Fe (mg/kg)	45.8±15.2^{a}	22.4±8.9^{b}	8.9±3.4^{c}	124.7	<0.001
Mn (mg/kg)	28.6±9.8^{a}	15.2±6.1^{b}	4.2±2.1^{c}	98.5	<0.001
Zn (mg/kg)	3.8±1.2^{a}	2.4±0.8^{b}	1.1±0.4^{c}	67.9	<0.001
Cu (mg/kg)	2.1±0.7^{a}	1.6±0.5^{b}	0.9±0.3^{c}	34.6	<0.001

Different letters indicate significant differences ($p < 0.05$)

3.4 Correlation Analysis

Correlation analysis revealed significant relationships between soil pH and nutrient availability (Table 4). Phosphorus showed a quadratic relationship with pH ($r^2 = 0.73$), confirming the optimum availability in neutral pH range. Micronutrients exhibited strong negative correlations with pH, with iron showing the strongest relationship ($r = -0.87$). Calcium and magnesium demonstrated strong positive correlations with pH, reflecting their abundance in alkaline soil conditions.

Table 4: Correlation coefficients between soil pH and nutrient availability

Nutrient	Correlation Coefficient (r)	Relationship Type	P-value
Phosphorus	0.12 (linear), 0.73 (quadratic)	Quadratic	<0.001
Potassium	0.28	Positive linear	0.002
Calcium	0.79	Positive linear	<0.001
Magnesium	0.71	Positive linear	<0.001
Iron	-0.87	Negative linear	<0.001
Manganese	-0.82	Negative linear	<0.001
Zinc	-0.74	Negative linear	<0.001
Copper	-0.68	Negative linear	<0.001

4. Discussion

4.1 pH-Dependent Nutrient Availability Mechanisms

The results confirm that soil pH serves as a master variable controlling nutrient availability through multiple mechanisms. The quadratic relationship observed for phosphorus availability reflects the complex chemistry governing P solubility across the pH spectrum [31]. In acidic conditions, phosphorus forms insoluble complexes with aluminum and iron, while in alkaline conditions, precipitation with calcium limits P availability [32]. The optimal pH range of 6.0-7.0 for phosphorus availability aligns with previous findings and represents a compromise between these competing fixation mechanisms.

The strong negative correlations between pH and micronutrient availability primarily result from precipitation and hydroxide formation under alkaline conditions [33]. Iron deficiency in alkaline soils is a well-documented phenomenon attributed to the formation of insoluble iron hydroxides and oxides [34]. The dramatic decrease in iron availability from acidic to alkaline soils (>80% reduction) highlights the critical importance of pH management for preventing iron chlorosis in sensitive crops.

Manganese availability patterns reflect similar precipitation mechanisms, with Mn^{2+} being the primary bioavailable form under acidic conditions [35]. As pH increases, manganese undergoes oxidation and precipitation, reducing plant uptake. The strong pH dependency of manganese availability has important implications for crop nutrition, particularly for acid-loving plants that require adequate manganese supply.

4.2 Practical Implications for Agricultural Management

The findings have significant implications for fertilizer management and soil amendment strategies. In acidic soils, liming programs should be carefully designed to raise pH to the optimal range (6.0-7.0) while avoiding over-liming that could induce micronutrient deficiencies [36]. The concurrent improvement in phosphorus availability and calcium supply through liming provides multiple benefits for crop nutrition.

For alkaline soils, management strategies should focus on maintaining adequate micronutrient supply through targeted fertilization or soil amendments [37]. The use of chelated micronutrients or acidifying amendments can help overcome the reduced availability of iron, zinc, and manganese in high pH soils. Organic matter additions can also improve micronutrient availability through chelation and pH buffering effects [38].

4.3 Regional and Crop-Specific Considerations

The distribution of pH conditions across the study sites reflects global patterns of soil acidification and alkalinization [39]. Acidic soils dominate in high-rainfall regions where intensive agriculture has accelerated acidification processes through nitrogen fertilization and crop removal [40]. These soils require sustained management attention to prevent further acidification and maintain productive capacity.

Alkaline soils, prevalent in arid and semi-arid regions, present different challenges related to micronutrient deficiencies and salt accumulation [41]. The higher electrical conductivity observed in alkaline soils indicates potential salinity issues that compound nutrient availability problems. Integrated management approaches addressing both pH and salinity are essential for optimizing crop production in these environments.

4.4 Environmental and Sustainability Considerations

Soil pH management has important environmental implications beyond crop production [42]. Acidic soils are associated with aluminum toxicity and increased potential for heavy metal mobility, while alkaline soils may contribute to nitrous oxide emissions and nutrient losses [43]. Sustainable pH management strategies must balance production goals with environmental protection objectives.

The increasing recognition of soil health as a comprehensive indicator of agricultural sustainability emphasizes the importance of maintaining optimal pH ranges [44]. Healthy soils with appropriate pH support diverse microbial communities, efficient nutrient cycling, and resilient crop production systems [45].

5. Conclusion

This comprehensive study demonstrates the critical role of soil pH in controlling nutrient availability across acidic and alkaline soil conditions. The research provides quantitative evidence for pH-dependent nutrient availability patterns and identifies optimal pH ranges for maximizing nutrient supply to crops. Key findings include:

1. **Optimal pH Range:** The pH range of 6.0-7.0 provides the most favorable conditions for overall nutrient availability, balancing macronutrient supply with micronutrient accessibility.
2. **Phosphorus Availability:** Phosphorus shows a distinct optimum curve with maximum availability in neutral pH conditions, declining significantly in both acidic and alkaline soils due to different fixation mechanisms.
3. **Micronutrient Dependencies:** Iron, manganese, zinc, and copper availability decrease dramatically with increasing pH, requiring targeted management strategies in alkaline soils.
4. **Management Implications:** Acidic soils benefit from carefully managed liming programs, while alkaline soils require micronutrient supplementation and pH modification strategies.

The results provide a scientific foundation for developing site-specific nutrient management recommendations and pH modification strategies. Future research should focus on investigating the temporal dynamics of pH-nutrient interactions and developing predictive models for nutrient availability under changing environmental conditions. Understanding these relationships is essential for maintaining agricultural productivity while promoting environmental sustainability in diverse soil conditions.

Effective soil pH management represents a fundamental component of sustainable agriculture, influencing not only current crop production but also long-term soil health and ecosystem functioning. The integration of pH management with precision agriculture technologies offers promising opportunities for optimizing nutrient use efficiency and reducing environmental impacts of agricultural systems.

6. References

1. Brady NC, Weil RR. The Nature and Properties of Soil. 15th ed. Upper Saddle River: Pearson Prentice Hall; 2017.
2. Havlin JL, Tisdale SL, Nelson WL, Beaton JD. Soil Fertility and Fertilizers: An Introduction to Nutrient Management. 8th ed. Upper Saddle River: Pearson; 2014.
3. Marschner P. Marschner's Mineral Nutrition of Higher Plants. 3rd ed. London: Academic Press; 2012.
4. Thomas GW. Soil pH and soil acidity. In: Sparks DL, editor. Methods of Soil Analysis Part 3: Chemical Methods. Madison: Soil Science Society of America; 1996. p. 475-490.
5. McLean EO. Soil pH and lime requirement. In: Page AL, editor. Methods of Soil Analysis Part 2: Chemical and Microbiological Properties. Madison: American Society of Agronomy; 1982. p. 199-224.
6. Lindsay WL. Chemical Equilibria in Soils. New York: John Wiley & Sons; 1979.
7. Sposito G. The Chemistry of Soils. 2nd ed. New York: Oxford University Press; 2008.
8. von Uexküll HR, Mutert E. Global extent, development and economic impact of acid soils. Plant Soil. 1995;171(1):1-15.
9. Kochian LV, Hoekenga OA, Piñeros MA. How do crop plants tolerate acid soils? Mechanisms of aluminum tolerance and phosphorous efficiency. Annu Rev Plant Biol. 2004;55:459-493.
10. Qadir M, Schubert S. Degradation processes and nutrient constraints in sodic soils. Land Degrad Dev. 2002;13(4):275-294.
11. Fageria NK, Baligar VC. Enhancing nitrogen use efficiency in crop plants. Adv Agron. 2005;88:97-185.
12. Alloway BJ. Zinc in Soils and Crop Nutrition. 2nd ed. Brussels: International Zinc Association; 2008.
13. Rengel Z. Availability of Mn, Zn and Fe in the rhizosphere. J Soil Sci Plant Nutr. 2015;15(2):397-409.
14. Truog E. The determination of the readily available phosphorus of soils. J Am Soc Agron. 1930;22:874-882.
15. Lucas RE, Davis JF. Relationships between pH values of organic soils and availabilities of 12 plant nutrients. Soil Sci. 1961;92(3):177-182.
16. Sims JT. Soil pH effects on the distribution and plant availability of manganese, copper, and zinc. Soil Sci Soc Am J. 1986;50(2):367-373.
17. Guo JH, Liu XJ, Zhang Y, *et al*. Significant acidification in major Chinese croplands. Science. 2010;327(5968):1008-1010.
18. Bolan NS, Hedley MJ, White RE. Processes of soil acidification during nitrogen cycling with emphasis on legume based pastures. Plant Soil. 1991;134(1):53-63.
19. Soil Survey Staff. Keys to Soil Taxonomy. 12th ed. Washington: USDA-Natural Resources Conservation Service; c2014.

20. McLean EO. Soil pH and lime requirement. In: Page AL, editor. Methods of Soil Analysis Part 2. Madison: American Society of Agronomy; 1982. p. 199-223.
21. Mehlich A. Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant. Commun Soil Sci Plant Anal. 1984;15(12):1409-1416.
22. Sumner ME, Miller WP. Cation exchange capacity and exchange coefficients. In: Sparks DL, editor. Methods of Soil Analysis Part 3. Madison: Soil Science Society of America; 1996. p. 1201-1229.
23. Lindsay WL, Norvell WA. Development of a DTPA soil test for zinc, iron, manganese, and copper. Soil Sci Soc Am J. 1978;42(3):421-428.
24. Keeney DR, Nelson DW. Nitrogen—inorganic forms. In: Page AL, editor. Methods of Soil Analysis Part 2. Madison: American Society of Agronomy; 1982. p. 643-698.
25. Nelson DW, Sommers LE. Total carbon, organic carbon, and organic matter. In: Sparks DL, editor. Methods of Soil Analysis Part 3. Madison: Soil Science Society of America; 1996. p. 961-1010.
26. Rhoades JD. Cation exchange capacity. In: Page AL, editor. Methods of Soil Analysis Part 2. Madison: American Society of Agronomy; 1982. p. 149-157.
27. Hinsinger P. Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: a review. Plant Soil. 2001;237(2):173-195.
28. McLaughlin MJ, Tiller KG, Naidu R, Stevens DP. Review: the behaviour and environmental impact of contaminants in fertilizers. Aust J Soil Res. 1996;34(1):1-54.
29. Guerinot ML, Yi Y. Iron: nutritious, noxious, and not readily available. Plant Physiol. 1994;104(3):815-820.
30. Alloway BJ. Heavy Metals in Soils: Trace Metals and Metalloids in Soils and their Bioavailability. 3rd ed. Dordrecht: Springer; 2013.
31. Hinsinger P, Plassard C, Tang C, Jaillard B. Origins of root-mediated pH changes in the rhizosphere and their responses to environmental constraints: a review. Plant Soil. 2003;248(1-2):43-59.
32. Sample EC, Soper RJ, Racz GJ. Reactions of phosphate fertilizers in soils. In: Khasawneh FE, editor. The Role of Phosphorus in Agriculture. Madison: American Society of Agronomy; 1980. p. 263-310.
33. Chaney RL. Zinc phytotoxicity. In: Robson AD, editor. Zinc in Soils and Plants. Dordrecht: Kluwer Academic Publishers; 1993. p. 135-150.
34. Chen Y, Barak P. Iron nutrition of plants in calcareous soils. Adv Agron. 1982;35:217-240.
35. Horst WJ, Marschner H. Effect of silicon on manganese tolerance of bean plants (*Phaseolus vulgaris* L.). Plant Soil. 1978;50(1-3):287-303.
36. Helyar KR, Porter WM. Soil acidification, its measurement and the processes involved. In: Robson AD, editor. Soil Acidity and Plant Growth. Sydney: Academic Press; 1989. p. 61-101.
37. Reed ST, Martens DC. Copper and zinc. In: Rechcigl JE, editor. Soil Amendments and Environmental Quality. Boca Raton: CRC Press; 1995. p. 131-200.
38. Stevenson FJ. Humus Chemistry: Genesis, Composition, Reactions. 2nd ed. New York: John Wiley & Sons; 1994.
39. Sumner ME, Noble AD. Soil acidification: the world story. In: Rengel Z, editor. Handbook of Soil Acidity. New York: Marcel Dekker; 2003. p. 1-28.
40. Bolan NS, Adriano DC, Curtin D. Soil acidification and liming interactions with nutrient and heavy metal transformation and bioavailability. Adv Agron. 2003;78:215-272.
41. Rengasamy P. World salinization with emphasis on Australia. J Exp Bot. 2006;57(5):1017-1023.
42. Goulding KWT. Soil acidification and the importance of liming agricultural soils with particular reference to the United Kingdom. Soil Use Manag. 2016;32(3):390-399.
43. Schroder JL, Zhang H, Girma K, *et al*. Soil acidification from long-term use of nitrogen fertilizers on winter wheat. Soil Sci Soc Am J. 2011;75(3):957-964.
44. Kibblewhite MG, Ritz K, Swift MJ. Soil health in agricultural systems. Philos Trans R Soc B. 2008;363(1492):685-701.
45. Mäder P, Fliessbach A, Dubois D, *et al*. Soil fertility and biodiversity in organic farming. Science. 2002;296(5573):1694-1697.