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Role of soil pH as a primary chemical indicator of soil health

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Abstract: -

It is commonly acknowledged that one of the most basic chemical factors influencing soil fertility and health is soil pH. It directly affects organic matter decomposition, heavy metal mobility, microbial community structure, and nutrient availability as a master variable. Examining its mechanistic influence on biogeochemical processes, its diagnostic value in soil quality assessment frameworks, and its practical implications for sustainable land management, this paper explores the pivotal function of soil pH as a major chemical indicator of soil health. Numerous studies have demonstrated that keeping soil pH in the ideal range of 6.0–7.0 maximises biological activity and nutrient usage efficiency. Agricultural production and ecosystem function are seriously threatened by soil acidification and alkalinisation, which are caused by both natural processes and human activity. The methods for measuring pH, monitoring techniques, and amendment procedures that are crucial for managing soil health are covered in the paper's conclusion.

1. Introduction:

A key component of agricultural sustainability and environmental resilience is soil health, which is described as the soil's ongoing ability to function as a vital living ecosystem that supports plants, animals, and people (Doran & Parkin, 1994). pH is the most crucial chemical parameter among the wide range of biological, physical, and chemical indicators used to evaluate soil health; it is frequently referred to as the "master variable" of soil chemistry (Brady & Weil, 2016).

Almost all chemical and biological processes that take place in the soil environment are impacted by soil pH, which is the negative logarithm of the hydrogen ion activity in the soil solution. It controls the movement of potentially hazardous elements, regulates the activity of soil microbes and

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enzymes, controls the availability and solubility of vital plant nutrients, and mediates the rates of organic matter decomposition and nutrient cycling.

Soil pH is often disregarded in normal soil monitoring programs outside of agricultural contexts, despite its crucial importance. The necessity to treat soil pH not only as a crop management tool but also as a primary diagnostic signal within comprehensive soil health assessment frameworks is highlighted by the expanding global challenges of soil degradation, intensive land use, and climate change.

The scientific underpinnings of soil pH as a primary chemical indicator of soil health are reviewed in this paper, along with its mechanistic function in soil processes, diagnostic significance, measurement and monitoring techniques, and management approaches to preserve or restore ideal pH levels.

2. Understanding Soil pH: Definition and Scale

A logarithmic scale from 0 to 14 is used to measure the pH of soil, with 7.0 being neutral, values below 7.0 being acidic, and values above 7.0 being alkaline. A change of one pH unit corresponds to a tenfold change in the concentration of hydrogen ions because the scale is logarithmic. This non-linear relationship has significant effects on soil chemistry since even slight pH changes can have a significant impact on biological activity and nutrient availability.

The majority of agricultural crops

Table 1. Soil pH classification and agricultural significance (adapted from Brady & Weil, 2016).

pH Range	Classification	Typical Soil Environment	General Agricultural Impact
< 4.5	Extremely Acidic	Peat bogs, heavy-rainfall tropics	Toxicity from Al and Mn; relatively few crops survive
4.5 – 5.5	Strongly Acidic	Highly leached forest soils	Nutrient deficiencies; acid-tolerant species only
5.5 – 6.0	Moderately Acidic	Many temperate croplands	Moderate nutrient availability
6.0 – 7.0	Slightly Acidic–Neutral	Optimal agricultural soils	Maximum nutrient availability, perfect for the majority of crops
7.0 – 7.5	Slightly Alkaline	Calcareous soils, arid regions	Slight reduction in P, Mn, Fe
7.5 – 8.5	Moderately Alkaline	Irrigated semi-arid soils	Fe, Zn, Cu deficiencies common
> 8.5	Strongly Alkaline	Sodic soils	Serious nutritional and structural issues

thrive in the pH range of 6.0 to 7.0, which is slightly acidic to nearly neutral and maximises the availability of both macronutrients and micronutrients. Even when overall soil nutrient stocks are sufficient, plant nutrition is hampered outside of this window; this condition is referred to as "chemical soil infertility."

3. Soil pH and Nutrient Availability

The control of plant-available nutrient concentrations is the most direct and important function of soil pH in agriculture. Precipitation-dissolution processes, adsorption-desorption equilibria, and the ionic speciation of elements in the soil solution are some of the mechanisms by which this impact functions.

3.1 Macronutrients

Nitrogen (N) availability is closely tied to soil pH through its control over microbial nitrification and denitrification rates. Optimal microbial activity converting ammonium to nitrate occurs between pH 6.0 and 8.0. Phosphorus (P) presents a characteristic bell-shaped availability curve, with maximum availability near pH 6.5. At lower pH, P is fixed by aluminum and iron oxides; at higher pH, calcium phosphate precipitates form. Potassium, calcium, and magnesium availability generally remain adequate across a moderately wide pH range but can be compromised at extremes.

3.2 Micronutrients

The behavior of micronutrients is highly reliant on pH, frequently in opposite ways. In acidic environments, iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and boron (B) become more soluble and sometimes poisonous, while in alkaline environments, they become less accessible. On the other hand, as pH rises, molybdenum (Mo) availability rises. Because of this different behavior, managing pH requires careful balancing, especially in soils where toxicities

Table 2. Nutrient availability as a function of soil pH.

Nutrient	Optimal pH Range	Constraint at Low pH	Constraint at High pH
Nitrogen (N)	6.0 – 8.0	Diminished microbiological activity	A rise in denitrification
Phosphorus (P)	6.5 – 7.5	Al and Fe fixation	Ca precipitation
Potassium (K)	6.0 – 7.5	Leaching in sandy soils	Generally sufficient
Iron (Fe)	4.0 – 6.5	Potential toxicity	Common deficiency
Manganese (Mn)	5.0 – 6.5	Toxicity below 5.5	Deficit more than 7.0
Zinc (Zn)	5.5 – 7.0	Moderate leaching	Strong fixation above 7.5
Molybdenum (Mo)	6.0 – 8.0	Severe deficiency < 5.5	Generally sufficient

and micronutrient deficits may coexist.

4. Soil pH and Biological Activity

Perhaps the most significant environmental filter influencing the composition and functional diversity of the soil microbial community is the pH of the soil. Most soil bacteria are neutrophilic and like pH values between 6.5 and 7.5. In acidic soils below pH 5.5, on the other hand, fungi tend to predominate and can withstand a greater variety. Plant disease control, organic matter breakdown, and nutrient cycling are all impacted by this pH-driven change in the bacteria:fungi ratio.

4.1 Enzyme Activity and Microbial Biomass

Numerous studies have shown that microbial biomass carbon, microbial respiration rates, and the activity of important soil enzymes including urease, phosphatase, and dehydrogenase are positively correlated with soil pH. Below pH 5.5, urease activity, which is essential for nitrogen cycling, is significantly suppressed. Similar to this, phosphatase activity peaks close to neutral pH and is necessary for the mineralization of organic phosphorus. One important way that pH reduces the effectiveness of nutrient cycling is by the inhibition of microbial enzymatic activity in acidic soils.

4.2 Nitrogen-Fixing and Nitrifying Bacteria

Rhizobium bacteria in legume root nodules fix nitrogen symbiotically, although this process is extremely sensitive to pH. The biological nitrogen supply that is the foundation of sustainable legume-based cropping systems is compromised when rhizobium populations are drastically decreased below pH 5.5 and nodule formation is impeded. The nitrogen capital of the ecosystem is further diminished by free-living nitrogen fixers and nitrifying bacteria (Nitrosomonas, Nitrobacter) that are equally vulnerable to soil acidification.

4.3 Soil Fauna and Earthworms

Earthworms and other soil macrofauna are essential for the formation of soil structure and the assimilation of organic materials. For life and reproduction, earthworms typically need soil pH levels above 5.0–5.5. Reduced bioturbation, poor drainage, and delayed organic matter processing are all consequences of acidification-driven declines in earthworm populations that eventually deteriorate the physical structure of the soil.

5. Soil pH and Toxic Element Mobility

Plant toxicity and food safety are significantly impacted by soil pH, which is the main regulator of heavy metal solubility and bioavailability. Aluminum (Al), manganese (Mn), cadmium (Cd), lead (Pb), nickel (Ni), and other potentially hazardous metals become much more soluble when pH falls below 5.5. The main growth-limiting factor in acid soils worldwide is aluminum toxicity, which directly prevents root elongation and hinders the uptake of nutrients and water.

On the other hand, heavy metals are efficiently immobilized by lowering the pH of the soil through liming, which lowers their plant-available fractions and groundwater leaching potential. The management of polluted soils makes extensive use of this pH-driven repair process. However, arsenic and some molybdate species can be mobilized by excessive alkalinization, indicating that pH control needs to be adjusted to site-specific contaminant profiles.

6. Using Soil pH as a Diagnostic Measure in Frameworks for Soil Health

Along with organic matter content, electrical conductivity, and nutrient concentrations, pH is a fundamental chemical indicator in all soil health assessment frameworks. Due to its integrative character across biological, chemical, and physical soil qualities, pH is recognized as a tier-one diagnostic variable by both the USDA's Soil Management Assessment Framework (SMAF) and the Cornell Comprehensive Assessment of Soil Health (CASH).

6.1 Scoring and Threshold Values

Depending on the kind of land use, pH is usually given ideal, sub-optimal, and critical threshold values in quantitative soil health scoring systems. Maximum scores are awarded to agricultural soils with an ideal pH of 6.0–7.0 for the majority of crops; deviations in either direction result in score penalties that are proportionate to the degree of the deviation. This method of scoring gives land managers a consistent, comparative measure of the chemical state of the soil at various locations and times of observation.

6.2 Integration with Other Indicators

pH interacts with and influences almost every other measure of soil health; it does not function in a vacuum. It affects microbial diversity indices, aggregate stability (via impacts on calcium and aluminum bridging), nitrogen mineralization dynamics, and soil organic matter decomposition rates (and consequently carbon storage). The classification of pH as a major chemical indicator rather than a secondary one is supported by this cross-indicator integration.

7. Causes of Soil pH Change

Understanding the mechanisms that gradually acidify or alkalinize soils is necessary to maintain the proper pH of the soil.

7.1 Natural Acidification

Rainfall-induced leaching of base cations (Ca, Mg, K, and Na), the buildup of organic acids from the breakdown of plant litter, the release of carbonic acid from root and microbial respiration ($CO2 + H2O$), and the oxidation of sulfide minerals in pyrite-bearing soils are the main causes of natural soil acidification. Continuous cultivation and areas with considerable rainfall intensify these processes.

7.2 Anthropogenic Acidification

The use of ammonium-based nitrogen fertilizers, which are the main cause of soil acidification in intensive agriculture, acid deposition from industrial pollution (sulfur dioxide, nitrogen oxides), the removal of basic cations from crop biomass, and irrigation with acidic water are all ways that human activity significantly speeds up soil acidification. Over the past 30 to 50 years, major cereal-growing regions have seen pH decreases of 0.5 to 1.5 units due to long-term cropping under large nitrogen inputs, which has resulted in widespread acidification of agricultural soils worldwide.

7.3 Alkalinization

Evapotranspiration surpassing rainfall and poor irrigation water quality are the main causes of soil alkalinization in arid and semi-arid regions, where soluble salts and sodium carbonate build up. Localized alkalinization can also result from excessive lime application and specific industrial waste disposal techniques.

8. Soil pH Measurement and Monitoring

Using soil pH as a trustworthy health indicator requires precise and consistent pH monitoring. Using a calibrated pH electrode, the typical laboratory procedure measures pH in a 1:1 or 1:2 soil:water suspension. In research settings, measurement in a 0.01 M calcium chloride (CaCl2) solution is preferable because it lessens variability caused by salt content and yields more consistent findings across seasons and moisture conditions.

8.1 Spatial Variability

Because of variations in parent material, drainage, organic matter content, and management history, soil pH can vary significantly within a field, hillslope, or landscape. This geographical heterogeneity can be mapped using precision agricultural techniques like electromagnetic induction surveys or dense grid sampling, allowing site-specific lime application that maximizes resource utilization and prevents over- or under-liming.

8.2 Temporal Observation

The pH of soil is a dynamic feature that varies over years to decades due to climate and management techniques. For agricultural soils, long-term monitoring programs advise measuring pH every three to five years, and for wild ecosystems, every five to ten years. Emerging technologies such as ion-selective field-effect transistors (ISFETs) and continuous pH sensors provide real-time pH monitoring in situ, creating new opportunities for dynamic soil health assessment.

9. Management of Soil pH

9.1 Acidic Soil Liming

The main minerals used to enhance soil pH are hydrated lime (Ca(OH)2), quicklime (CaO), dolomitic limestone (CaCO3·MgCO3), and agricultural lime (calcium carbonate, CaCO3). The amount of lime required to get a certain pH is determined by the soil's buffering capacity, which is influenced by cation exchange capacity (CEC), organic matter, and clay concentration. For the same pH change, clay-rich soils with high buffering capacity need a lot more lime than sandy soils with low CEC.

9.2 Alkaline Soil Acidifying Amendments

Elemental sulfur, sulfuric acid, ammonium sulfate, and iron sulfate can be used to reduce pH when it is too high. Soil bacteria (Thiobacillus) oxidize elemental sulfur to produce sulfuric acid, a slow but economical acidification process. To prevent over-acidification, these therapies need precise rate calculation and frequent monitoring.

9.3 Management of Organic Matter

Compost, manure, cover crops, and crop residue retention are examples of organic matter inputs that can buffer soil pH against abrupt changes, lowering rates of acidification and alkalinization. Organic matter's humic compounds serve as amphoteric buffers, offering the ability to exchange protons and hydroxyl ions. Thus, a key element of a pH stabilization plan is long-term organic matter management.

10. Conclusion

As the main chemical indicator integrating nutrient cycle, biological activity, hazardous element dynamics, and organic matter processes, soil pH holds a special and central place in soil health science. No other single parameter has such a wide and simultaneous impact on the physical, chemical, and biological aspects of soil function, hence its categorization as a "master variable" is well-founded.

One of the biggest and least recognized risks to food security and ecosystem sustainability is the global trend of agricultural soil acidification, which is caused by the use of nitrogen fertilizers and the removal of base cations. On the other hand, alkalinization presents equally significant difficulties in dry irrigated systems. There is strong scientific evidence to support making soil pH monitoring and management a top priority in sustainable land management.

Future studies should concentrate on establishing pH-integrated soil health indices that are applicable to a variety of land use types, increasing the accuracy and accessibility of in-situ pH monitoring systems, and calculating the ecological and financial returns on pH management efforts. Embedding soil pH as an obligatory indication in national and international soil health monitoring frameworks would constitute a huge step toward maintaining and repairing one of humanity's most critical natural resources.

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