## Review Article

# The Role of Soil pH in Plant Nutrition and Soil Remediation

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In the natural environment, soil pH has an enormous influence on soil biogeochemical processes. Soil pH is, therefore, described as the "master soil variable" that influences myriads of soil biological, chemical, and physical properties and processes that affect plant growth and biomass yield. This paper discusses how soil pH affects processes that are interlinked with the biological, geological, and chemical aspects of the soil environment as well as how these processes, through anthropogenic interventions, induce changes in soil pH. Unlike traditional discussions on the various causes of soil pH, particularly soil acidification, this paper focuses on relationships and effects as far as soil biogeochemistry is concerned. Firstly, the effects of soil pH on substance availability, mobility, and soil biological processes are discussed followed by the biogenic regulation of soil pH. It is concluded that soil pH can broadly be applied in two broad areas, i.e., nutrient cycling and plant nutrition and soil remediation (bioremediation and physicochemical remediation).

## 1. Introduction

To many, soil pH is only essential for the chemistry and fertility of soils. However, the recognition of soil functions beyond plant nutrient supply and the role soil as a medium of plant growth required the study of the soil and its properties in light of broader ecosystem functions through a multidisciplinary approach. This allows scientists to view processes from landscape to regional and global levels. One process that denotes the multidisciplinary approach to soil science is soil biogeochemistry, which studies biogeochemical processes. The ecosystem functions of soil, to some extent, have a strong relationship with soil biogeochemical processes, which are linkages between biological, chemical, and geological processes [1]. The soil is the critical element of life support systems because it delivers several ecosystem goods and services such as carbon storage, water regulation, soil fertility, and food production, which have effects on human well-being [2–4]. These ecosystem goods and services are broadly categorized as supporting, provisioning, regulating, and cultural services [5]. According to the Millennium Ecosystem Assessment [5], the provisioning and regulating functions are said to have the greatest impact on the components of human well-being in terms of safety, the basic material for a good life, health, and good social relations.

In the natural environment, the pH of the soil has an enormous influence on soil biogeochemical processes. Soil pH is, therefore, described as the "master soil variable" that influences myriads of soil biological, chemical, and physical properties and processes and processes that affect plant growth and biomass yield [6, 7]. Soil pH is compared to the temperature of a patient during medical diagnoses because it readily gives a hint of the soil condition and the expected direction of many soil processes (lecture statement, Emeritus Prof. Eric Van Ranst, Ghent University). For instance, soil pH is controlled by the leaching of basic cations such as Ca, Mg, K, and Na far beyond their release from weathered minerals, leaving $H^+$ and $Al^{3+}$ ions to dominant exchangeable cations; the dissolution of $CO_2$ in soil water producing carbonic acid, which dissociates and releases $H^+$ ions; humic residues from the humification of soil organic matter, which produces high-density carboxyl and phenolic groups that dissociate to release $H^+$ ions; nitrification of $NH_4^+$ to $NO_3^-$ produces $H^+$ ions; removal of N in plant and animal products; and inputs from acid rain and N uptake by plants [8]. On the other

hand, pH controls the biology of the soil as well as biological processes. Consequently, there is a bidirectional relationship between soil pH and biogeochemical processes in terrestrial ecosystems, particularly in the soil. In this sense, the soil pH influences many biogeochemical processes, whereas some biogeochemical processes, in turn, influence soil pH, to some extent, as summarised in Figure 1.

For many decades, intensive research has revealed that soil pH influences many biogeochemical processes. Recent advances in research have made intriguing revelations about the important role of soil pH in many soil processes. This important soil property controls the interaction of xenobiotics within the three phases of soil as well as their fate, translocation, and transformation. Soil pH, therefore, determines the fate of substances in the soil environment. This has implications for nutrient recycling and availability for crop production, distribution of harmful substances in the environment, and their removal or translocation. This functional role of soil pH in soil biogeochemistry has been exploited for the remediation of contaminated soils and the control of pollutant translocation and transformation in the environment. Unfortunately, in many studies, soil pH is often measured casually as a norm without careful consideration for its role in soil. This paper seeks to explore the importance of pH as an indicator of soil biogeochemical processes in environmental research by discussing the biogeochemical processes that are influenced by soil pH, the biogeochemical processes that also control soil pH, and the relevance of the relationship for future research, planning, and development.

## 2. Biogeochemical Processes Influenced by Soil pH

*2.1. Substance Translocation.* Simultaneously, in accordance with biochemical changes, physicochemical processes, including dissolution, precipitation, adsorption, dilution, volatilization, and others, influence leachate quality [9].

*2.1.1. Trace Element Mobility.* Soil pH controls the solubility, mobility, and bioavailability of trace elements, which determine their translocation in plants [10]. This is largely dependent on the partition of the elements between solid and liquid soil phases through precipitation-dissolution reactions [10, 11] as a result of pH-dependent charges in mineral and organic soil fractions. For instance, negative charges dominate in high pH whereas positive charges prevail in low pH values [12]. Additionally, the quantity of dissolved organic carbon, which also influences the availability of trace elements, is controlled by soil pH. At low pH, trace elements are usually soluble due to high desorption and low adsorption. At intermediate pH, the trend of trace element adsorption increases from almost no adsorption to almost complete adsorption within a narrow pH range called the pH-adsorption edge [13]. From this point onwards, the elements are completely adsorbed [13]. For instance, Bradl [13] found that at pH 5.3, the adsorption of Cd, Cu, and Zn onto a sediment composite consisting of Al-, Fe-, and Si-oxides was 60%, 62%,
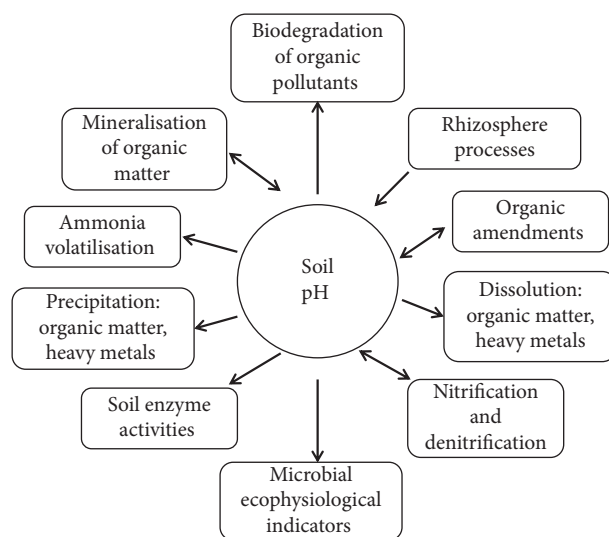


FIGURE 1: Some biogeochemical processes and their relations with soil pH.

and 53%, respectively. In contrast, he found that 50% of Cd and Zn sorbed onto humic acids between pH 4.8–4.9 [13]. The fate of readily available trace elements depends on both the properties of their ionic species formed in the soil solution and that of the chemical system of soil apart from soil pH itself [14]. Research has established that with increasing soil pH, the solubility of most trace elements will decrease, leading to low concentrations in soil solution [14]. Any increase or decrease in soil pH produces distinct effects on metal solubility. This may probably depend on the ionic species of the metals and the direction of pH change. Rengel [15] observed that the solubility of divalent metals decreases a hundred-fold while trivalent ones experience a decrease of up to a thousand-fold. In contrast, Förster [10] found that a decrease in soil pH by one unit resulted in a ten-fold increase in metal solubility. In an experiment, he observed that at pH 7, only about $1 \, mg \, Zn \cdot L^{-1}$ of the $1200 \, mg \cdot kg^{-1}$ total Zn content was present in soil solution. At pH 6, the concentration reached $100 \, mg \, Zn \cdot L^{-1}$ while at pH 5, $40 \, mg \, Zn \cdot L^{-1}$ was present. Aside from adsorption, trace element concentrations at high soil pH may also be caused by precipitation with carbonates, chlorides, hydroxides, phosphate, and sulphates [11, 16]. Apatite and lime applied to soils produced the highest effect on pH and simultaneously decreased the concentrations of available, leachable, and bioaccessible Cu and Cd [16].

*2.1.2. Mobility of Soil Organic Fractions.* Soil organic matter exists in different fractions ranging from simple molecules such as amino acids, monomeric sugars, etc. to polymeric molecules such as cellulose, protein, lignin, etc. These occur together with undecomposed and partly decomposed plant and microbial residues [17]. The solubility and mobility of the fractions differ during and after decomposition and could lead to the leaching of dissolved organic carbon and nitrogen in some soils. Dissolved organic carbon is defined as the size of organic carbon that passes through a 0.45 mm

diameter filter [18]. Soil pH increases the solubility of soil organic matter by increasing the dissociation of acid functional groups [19] and reduces the bonds between the organic constituents and clays [20]. Thus, the content of dissolved organic matter increases with soil pH and consequently mineralizable C and N [20]. This explains the strong effects of alkaline soil pH conditions on the leaching of dissolved organic carbon and dissolved organic nitrogen observed in many soils containing substantial amounts of organic matter [19, 21]. The same observation has been made on the dissolved organic carbon concentration in peatland soils [22]. The pH-dependence of dissolved organic carbon concentration gets more pronounced beyond pH 6 [23].

Within the pH condition in a specific soil system, the solubility of organic matter is strongly influenced by the type of base and is particularly greater in the presence of monovalent cations than with multivalent ones [23]. According to Andersson and Nilsson [24] and Andersson et al. [19], soil pH controls the solubility of organic matter in two major ways: (i) its influence on the charge density of the humic compounds, and (ii) either the stimulation or repression of microbial activity. The former is found to be more pronounced than the latter [19].

## 2.2. Soil Biological Processes

### 2.2.1. Microbial Ecophysiological Indicators.
Ecophysiology is an interlinkage between cell-physiological functioning under the influence of environmental factors [25]. It is estimated using the metabolic quotient ($qCO_2$) as an index [25] to show the efficiency of organic substrate utilization by soil microbes in specific conditions [26]. A decrease in microbial community respiration makes C available for more biomass production, which yields higher biomass per unit [27]. The metabolic quotient is, therefore, described as a cell-physiological entity that reflects changes in environmental conditions [25]. This implies that any change in environmental conditions towards the adverse state will be indicated by the index [25]. This is controlled by soil pH [28]. Soil pH as a driving force for microbial ecophysical indices stems from its influence on the microbial community together with the maintenance demands of the community [28] and was among the predictors of the metabolic quotient [29, 30]. The metabolic quotient was found to be two-and-a-half times higher in low pH soils compared to neutral pH soils [28]. This has been associated with the divergence of the internal cell pH (usually kept around 6.0) from the surrounding pH conditions, which increases the maintenance requirements and reduces total microbial biomass produced [25].

It is observed from the literature that soil pH conditions required for microbial activity range from 5.5–8.8 [26, 31, 32]. Thus, soil respiration often increases with soil pH to an optimum level [26]. This also correlates with microbial biomass C and N contents, which are often higher above pH 7 [26]. In low pH conditions, fungal respiration is usually higher than bacterial respiration and the vice versa [25] because fungi are more adapted to acidic soil conditions than bacteria.

### 2.2.2. Soil Enzyme Activities.
Extracellular enzymes are produced by soil microorganisms for the biogeochemical cycling of nutrients [33]. Soil pH is essential for the proper functioning of enzyme activity in the soil [34, 35], and may indirectly regulate enzymes through its effect on the microbes that produce them [36]. However, there are myriad of enzymes in biological systems which assist in the transformation of various substances. Besides, enzymes are of different origins and with differing degrees of stabilization on solid surfaces. Thus, the pH at which they reach their optimum activity (pH optima) is likely to differ [33]. It is striking that enzymes that act on the same substrates could vary considerably in their pH optima. This is evident in phosphorus enzymes, which have both acid and alkaline windows of functioning in the range of pH 3–5.5 and pH 8.5–11.5 [33]. In a study on the optimum pH for specific enzyme activity in soils from seven moist tropical forests in Central Panama, Turner [33] classified enzymes into three groups depending on their pH optima as found in the soils. These were: (a) enzymes with acidic optima that appeared consistent among soils, (b) enzymes with acidic pH optima that varied among the soils, and (c) enzymes with optima in both acid and alkaline soil pH. Stursova and Walker [37] found that organophosphorus hydrolase has optimal activity at higher pH. For instance, glycosidases have an optimal pH range between 4 and 6 compared to proteolytic and oxidative enzymes whose optima was between 7 and 9 [35, 36, 38]. Shifts in microbial community composition could potentially influence enzyme production if different microbial groups require lower nutrient concentrations to construct biomass, or have enzymes which differ in affinity for nutrients [39].

### 2.2.3. Biodegradation.
Soil microorganisms are described as ecosystem engineers involved in the transformation of substances in the soil. One of such transformations is biodegradation, a process through which microbes remediate contaminated soils by transforming toxic substances and xenobiotics into least or more toxic forms. Biodegradation is the chemical dissolution of organic and inorganic pollutants by microorganisms or biological agents [34, 40]. Like many soil biological processes, soil pH influences biodegradation through its effect on microbial activity, microbial community and diversity, enzymes that aid in the degradation processes as well as the properties of the substances to be degraded. Soil pH was the most important soil property in the degradation of atrazine [41]. Generally, alkaline or slightly acid soil pH enhances biodegradation, while acidic environments pose limitations to biodegradation [34, 37, 42]. Usually, pH values between 6.5 and 8.0 are considered optimum for oil degradation [43]. Within this range, specific enzymes function within a particular pH spectrum. For instance, the pesticide fenamiphos degraded in two United Kingdom soils with high pH (>7.7) and two Australian soils with pH ranging from pH 6.7 to 6.8. The biodegradation process rather slowed down in three acidic United Kingdom soils (pH 4.7 to 6.7) in 90 days after inoculation [42]. Xu [44] found some strains of bacteria isolated from petroleum-contaminated soil in northern China

being able to degrade over 70% of petroleum at pH 7 and 9. In a degradation experiment involving polycyclic aromatic hydrocarbons (PAHs), half of the PAHs degraded at pH 7.5 within seven days representing the highest amount degraded [34]. This was associated with the highest bacterial populations [34]. Furthermore, Houot et al. [41] found increased degradation of atrazine in French and Canadian soils, which occurred with increased soil pH. They observed maximum soil respiration in atrazine-contaminated soils at soil pH values higher than 6.5 compared to those with soil pH value less than 6.0 where metabolites rather accumulated.

*2.2.4. Mineralization of Organic Matter.* Organic matter mineralization is often expressed as carbon (C), nitrogen (N), phosphorus (P), and sulphur (S) mineralization through microbial action. Soil pH controls mineralization in soils because of its direct effect on the microbial population and their activities. This also has implications for the functions of extracellular enzymes that aid in the microbial transformation of organic substrates. Additionally, at a higher soil pH, the mineralizable fractions of C and N increase because the bond between organic constituents and clays is broken [20]. In a study on the mineralization of C and N in different upland soils of the subtropics treated with different organic materials, Khalil et al. [45] found that soil pH and C/N ratio were responsible for 61% of the decomposition rate, with corresponding increases in $CO_2$ effluxes, net N mineralization, and net nitrification in alkaline than in acid soils. Similar results had earlier on been obtained by Curtin et al. [20].

*2.2.5. Nitrification and Denitrification.* Nitrification and denitrification are important nitrogen transformation processes of environmental concern. Like many of the biogeochemical processes, the processes, to a large extent, are controlled by soil pH. Nitrification involves the microbial conversion of ammonium to nitrate. It generally increases with increasing soil pH but reaches an optimum pH [45–47]. In a four-year study, Kyveryga et al. [47] observed that soil pH range of 6 to 8 strongly influenced the nitrification rates of fertilizer N. Generally, the nitrification rate decreases at lower soil pH values. In some soils, nitrification and nitrification potential substantially decrease or are negligible below a pH value of 4.2. However, nitrification may still occur even below pH 4.14, suggesting that ammonia-oxidizing and nitrifier communities might remain active at low soil pH [48].

Denitrification is the microbiological process in which oxidized N species such as nitrate ($NO_3^-$) and nitrite ($NO_2^-$) are reduced to gaseous nitric oxide (NO), nitrous oxide ($N_2O$), and molecular nitrogen ($N_2$) under limited oxygen conditions [49]. Soil pH affects denitrification rate, potential denitrification, and the ratio between the two main products of denitrification ($N_2O$ and $N_2$). The ratio has an inverse relation with soil pH [49]. At pH values below 7, $N_2O$ was the main denitrification product whereas $N_2$ prevailed at pH values above 8 [49]. Sun et al. [50] discovered that soil pH was the best predictor of denitrification rate where the ratio of $N_2/N_2O$ increased exponentially with an increase in soil pH. This is because low pH prevents the assembly of functional nitrous oxide reductase, the enzyme reducing $N_2O$ to $N_2$ in denitrification [15, 20] and this mostly depends on the natural soil pH [49]. However, the soil pH at which the highest activity of nitrous oxide reductase occurred was around pH 7.3. This occurred in soils amended with potassium hydroxide (KOH) [51]. This suggests the inhibition of denitrification at high pH, particularly up to pH 9 [50]. Furthermore, maximum denitrification of between 68% and 85% occurred in a sandy and a loamy soil with pH 5.2 and 5.9, respectively [52]. The optimum pH for long-term potential denitrification was between 6.6 and 8.3. Additionally, the short-term denitrifying enzyme activity depended on the natural soil pH [49]. The effect of soil pH on denitrification is partly due to pH controls over the denitrifying microbial populations. The population size of the resident nitrate-reducing bacterial population increased dramatically when the pH of the acid soil was increased [53].

*2.2.6. Ammonia Volatilization.* The volatilization of ammonia is a phenomenon that occurs naturally in all soils [54] and has been attributed to the dissociation of $NH_4^+$ to $NH_3$ and $H^+$ shown in equation (1) [55]

$$NH_4^+ \longleftrightarrow NH_3 + H^+ \qquad (1)$$

The dissociation approaches equilibrium through the acidification of the medium. The rate of acidification depends on the initial and final concentrations of ammonium as well as on the buffering capacity of the medium [55]. When solution pH increases above 7, $H^+$ is consumed in the reaction. Thus, the dissociation of ammonium to ammonia in equation (1) will favour ammonia volatilization. In neutral and acid soils, $NH_4^-$ containing fertilizers are less subject to $NH_3$ loss than urea and urea-containing fertilizers [54]. However, the degree will also depend on the specific fertilizer and its effect on soil pH. In a study involving ammonia volatilization from an alkaline salt-affected soil cultivated with rice, Li et al. [56] found that ammonia volatilization increased rapidly with pH and peaked at pH 8.6. Ammonia volatilization is strongly correlated with pH and calcium carbonate, which suggested that the soil pH was a key factor in ammonia volatilization because calcium carbonate increases soil pH which in turn controls the concentration of ammonia and ammonium in soil solution [57].

## 3. Biogenic Regulation of Soil pH

Soil biological processes from living organisms and biochemical transformations of the remains of dead organisms induce changes in soil pH. This can either occur through the direct effect of biochemical processes occurring in the living organisms in the soil system, mostly through rhizosphere processes or through the direct and indirect effects of applied organic residues, whether in unburnt, burnt, or charred forms as well as their decomposition.

*3.1. Rhizosphere Processes.* The rhizosphere is the volume of soil in the neighbourhood of roots that is influenced by root and microbial activities [58–60] Hiltner 1904 cited by [60]. It is a longitudinal and radial gradient [61], ranging from 0 to 2.0 mm from the root mat [62, 63]. In this small soil volume, roots take up water and nutrients, undergo root elongation and expansion, release exudates, respire, and thus have higher microbial activity [59, 63]. Through some of these biological processes, plant roots have the ability to induce pH changes in the rhizosphere either by releasing protons ($H^+$) or hydroxyl ions ($OH^-$) to maintain ion balance [58, 64], depending on the nutritional status of the plants [65]. Therefore, rhizosphere pH could increase or decrease depending on the prevailing process and types of ions released.

Plant root-induced soil pH change in the rhizosphere is controlled by specific processes and factors such as (i) ion uptake coupled with the release of inorganic ions that maintain electroneutrality, (ii) the excretion of organic acid anions, (iii) root exudation and respiration, (iv) redox-coupled processes, (v) microbial production of acids after the assimilation of released root carbon, and (vi) plant genotype [58, 59]. Surprisingly, roots have a greater tendency to raise the pH of the rhizosphere rather than lower it [65, 66]. The dominant mechanism responsible for pH changes in the rhizosphere is plant uptake of nutrients in the form of cations and anions [58, 59, 65], primarily due to plant uptake of the two major forms of inorganic nitrogen ($NH_4^+$ and $NO_3^-$), which is usually taken up in large quantities [59]. Nitrogen is taken up by plants in three major forms: ammonium ($NH_4^+$), nitrate ($NO_3^-$), and molecular nitrogen ($N_2$) [59], although amino acids can also be taken up [58]. The uptake of each of the three forms of nitrogen accompanies the release of corresponding ions to maintain electroneutrality in the rhizosphere. When nitrate dominates in soil or when its uptake dominates, plants must release bicarbonate ($HCO_3^-$) or hydroxyl ions ($OH^-$) to maintain electrical neutrality across the soil-root interface resulting in rhizosphere pH increase [58, 59, 64]. In contrast, protons are released by plants in response to $NH_4^+$ uptake, causing a decrease in rhizosphere pH [58, 62]. It has been revealed that 15, 6, and 0%, respectively, of the $NH_4^-$ N from the total N present in the soil is required to decrease rhizosphere pH decrease by 1.2 units, maintain it, or increase it by 0.4 pH unit [62].

The extent of effects of the processes and factors controlling rhizosphere pH change depends on plant species and growth stages [65]. For instance, in a study on rhizosphere acidification interactions, Faget et al. [67] found differences between rhizosphere acidification in maize (*Zea mays* L.) and beans (*Phaseolus vulgaris* L.). Maize initially acidified the rhizosphere and gradually alkalized it over time while beans showed opposite effects. They found an interaction effect of the two plant species on the rhizosphere pH change whereby the degree of acidification or alkalization was weaker when roots grew within the same neighbourhood than when the roots were not growing near each other. However, the rhizosphere pH changes with time as a result of variable uptake of nitrogen ions, plant species, and their growth stages of the

plants [67]. This was revealed in an experiment on apple trees (*Malus pumila* Miller), buckwheat (*Fagopyrum esculentum* Moench), corn (*Zea mays* L.), cowpeas (*Vigna unguiculata* (L) Walp.), kaffir lime (*Citrus hystrix* DC.), lettuce (*Lactuca sativa* L.), pine trees (*Pinus* sp. L.), and wheat (*Triticum aestivum* L.), where Metzger [66] found maximum concentrations of $HCO_3^-$ in the rhizosphere during the blooming and fruiting stages (Figure 2), which was 10–29% higher compared to the bulk soil. The concentrations of $HCO_3^-$ in the rhizosphere of the plants was in the order, lettuce = buckwheat > pine > apple > kaffir > cowpeas > corn > wheat. These values were much lower than those obtained in the rhizosphere of soybean (Glycine max (L.) Merr.) [64]. Furthermore, Turpault et al. [59] found that 93% of $NO_3$-N was taken up by a Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands during April–September compared to 83% uptake during the October-March period. This likely increased rhizosphere pH and implies that during periods of low nitrate uptake, soil pH may decrease due to buffering or due to a response to the uptake of $NH_4^-$.

*3.2. Raw and Combusted Organic Materials.* When unburnt organic materials or raw plant residues are applied to the soil, the pH increases to a peak and decrease afterwards. For instance, Forján et al. [68] found initial increases in soil pH when they applied a mixture of sludge from a bleach plant, urban solid waste and mine wastes, and a mixture of sludge from a purification plant, wood chips, and remnants from agri-food industries to the soil. Furthermore, the addition of young Kikuyu (*Pennisetum clandestinum* L.) shoots also increased soil pH by up to one pH unit [69]. The major causes of this pH change is due to the (i) release of excess residue alkalinity attributed to the basic cations such as Ca, K, Mg, and Na [70]; (ii) decarboxylation of organic anions that occurs during C mineralisation, causing the consumption of protons and release of $OH^-$ [71, 72]; (iii) ammonification of the residue N; (iv) nitrification of mineralised residue N; and (v) association/dissociation of organic compounds [70]. These processes are determined by the quantity applied and the prevailing soil and environmental conditions [70]. According to Xu et al. [70]; direct chemical reactions and oxidation of the organic anions during residue decomposition are the main mechanisms involved in organic anion-induced soil pH increase. Additionally, organic anions and other negatively charged chemical functional groups present in organic matter can undergo association reactions with $H^+$ ions [71, 73].

The increase in soil pH after residue application also depends on the type of residue (either from monocots or dicots), which is related to the amount of alkalinity present, residue quality (C/N ratio), the rate of residue application and decomposition, the initial pH, and buffering capacity of the soil [70, 71]. Different residues have different chemical and biochemical compositions, which determine the processes responsible for soil pH change. This was detected in an incubation experiment involving three soils and five different residue types where soil pH increased according to lucerne > chickpea > medic > high-N wheat > low-N wheat [70].
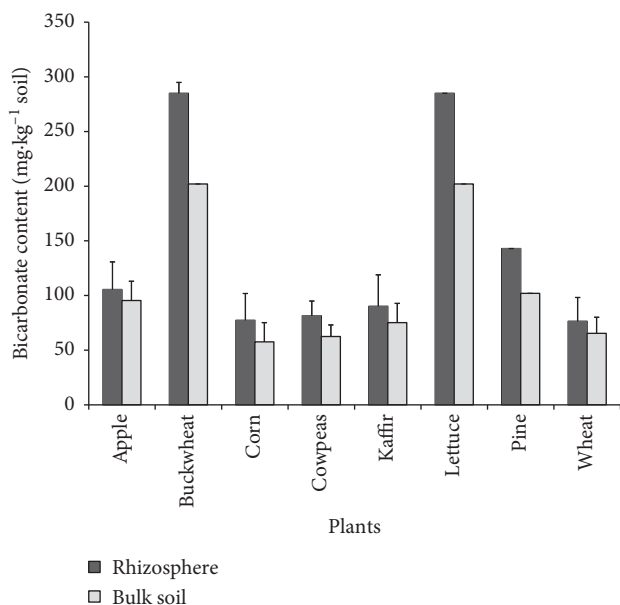
FIGURE 2: The compositions of bicarbonate as found in the rhizosphere and bulk soil of some plants grown in a greenhouse. Error bars are ± one standard deviation ($n = 2$ to 34). Lettuce and pine had only data one data point each and could not be presented with error bars (data from [66]).

Furthermore, in a 59-day laboratory incubation [71] and field experiments [74], it was found that the magnitude of soil pH increase following residue amendment was in the order chickpea > canola > wheat [71, 74]. They observed that 40–62% of soluble alkalinity in canola and chickpea residues were responsible for the pH increases. It is obvious from these, and many other studies [69], that the residues of dicots, particularly legumes, have high alkalinity and produce larger effects on soil pH change than monocots. The pH increase after residue addition often reaches a peak and declines thereafter as a result of nitrification. Residues with low carbon-nitrogen (C/N) ratios are often associated with sharp pH decline after a certain period and the extent varies with soil type and soil buffering capacity [70, 71, 74], whereas those with high C/N ratios produce smaller pH increase, or none at all [70].

The initial pH and buffering capacity of soils receiving plant residues have a profound role in the extent of pH change after application. For instance, three soil types of different initial soil pH, namely, Wodjil sandy loam with pH(CaCl$_2$) 3.87, Bodallin sandy loam soil with pH 4.54, and Lancelin sandy soil with pH 5.06, were incubated with residues of chickpea, lucerne, medic, high-N wheat, and low-N wheat. Thereafter, the pH increased by about 3.3 units with lucerne in the Wodjil soil (3.87), 1.6 with chickpea, 1.5 with medic, and 0.5 with high-N wheat, and no increase with low-N wheat. The pH increased and peaked at 42 days of incubation for Bodallin and Wodjil sandy loams followed by a decline whereas, in the Lancelin sandy soil, the pH peaked at day 14 before declining [70]. In another incubation study [71], a Podzol with an initial pH of 4.5 and a Cambisol with an initial pH of 6.2 were amended with residues of canola, chickpea, and wheat. For all the residues, the pH increase in the moderately acidic Cambisol was up to sixfold larger than

in the more acidic Podzol. This peaked at 14 days after application and declined afterwards. However, in a field study on the same soils [74], the application of chickpea residue increased soil pH by 1.3 units in both soils and reached a maximum at 3 months, whereas canola residue increased pH by 0.82 and 1.02 units in the Podzol and Cambisol, respectively, and reached a maximum pH at 9 months.

Similar to unburnt organic materials, burnt or charred plant residues contain a larger amount of alkalinity due to the volatilization of organic constituents under thermal conditions leading to the concentration of alkaline constituents. The actual alkalinity depends on the type of biomass involved, their origin, and burnt temperature. Burnt and charred forms of organic materials include biochar and ash. Biochar is a solid consistent product pyrolysis, while ash is a loose powdery material obtained by combustion. The pH of biochar produced at 500–600°C was 6.4–9.3 and showed a strong relationship with the total alkalinity (i.e., organic and inorganic alkalinities) [75]. The inorganic alkalinity increased with increasing pyrolysis temperature and with increasing divalent cation contents [75] because the organic constituents volatilize during pyrolysis. This alkalinity of biochar neutralizes acidity and increases soil pH depending on the amount of alkalinity and soil buffering capacity [76]. Biomass ash contains substantial alkalinity, which is often expressed as percent calcium carbonate equivalence (% CCE). It ranges from 17–95% [77, 78]. Similarly to biochar, the combustion temperature has effects on the alkalinity of biomass aside the biomass type and source. Recently, Neina et al. (submitted) found that ash from charcoal had higher CCE, pH, and K contents than firewood ash. Depending on the alkalify and buffering capacity of the soil receiving the biomass ash, soil pH increase can be high or low. For instance, in two Ghanaian Acrisols, biomass ash applied at 2.5 g·kg$^{-1}$ soil increased soil pH by about 1 unit after 12 weeks of laboratory incubation [79]. This pH change is mostly short-lived due to other biogeochemical processes.

## 4. Conclusions

The content of this paper highlights the role of soil pH as a master soil variable that has a bidirectional relationship with soil biogeochemical processes. Although not all biogeochemical processes were discussed in this paper, those discussed have substantial influences on soil health, nutrient availability, pollution, and potential hazards of pollutants as well as their fate in the food chain. The mobility of unwholesome substances through the hydrological cycle cannot be overlooked here because of the intimate relationship between soil and water. Thus, an understanding of this can form a basis and a guide to decisions and choices of soil management, remediation, rehabilitation, and the maintenance of soil quality. The observed soil pH-biogeochemistry relationships provide insight for future applications for increased yields for specific crops through nutrient recycling and availability, which enhances crop growth. The transient rhizosphere soil pH could also be used to enhance the availability of certain nutrients in certain soil conditions

[80]. More importantly, soil pH could be useful for soil pollution control through the distribution and removal of harmful substances from systems. For instance, the mineralization and degradation processes such as those of C and N mineralisation and the degradation of pesticide occur between pH 6.5 and 8, while the maximum degradation of petroleum and PAHs occur between pH 7 and 9. These, as well as pH maxima for various microbial enzymes, could be utilized in many soil remediation strategies, particularly in bioremediation. Ultimately, soil pH can broadly be applied in two broad areas, i.e., nutrient cycling and plant nutrition and soil remediation (bioremediation and physicochemical remediation).

## Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this article.

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