**IMPACT OF SOIL pH ON NUTRIENT UPTAKE BY CROP PLANTS**

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**INTRODUCTION**

Soil pH is one of the most indicative measurements of the chemical properties of soil, which exerts far-reaching and potentially favorable or adverse effects on the growth and nutrient uptake by crop plants.

**SOIL pH–INDUCED STRESS**

The pH of the growth medium has significant effects on the properties of soils and consequently on the nutrient uptake by crop plants. Soil pH is one of the most indicative measurements of the chemical properties of soil. Whether the soil is acidic, neutral, or basic has much to do with the solubility of various compounds, the relative bonding of ions to exchange sites, and the activity of various microorganisms in the soil systems. Thomas [1] noted that three soil pH ranges are particularly informative: a pH less than 4 indicates the presence of free acids generally from oxidation of sulfides; a pH less than 5.5 suggests the likely occurrence of exchangeable Al; and a pH of 7.8 to 8.2 indicates the presence of calcium carbonate, an important agent of calcareous soil.

Soils with pH values ranging from 4 to 7 [2] are extensively distributed throughout the tropical and subtropical regions of the world. Soils with pH values less than 4 also exist and are commonly found as acid sulfate soils and in mine soils. Plant growth in acid soils may be limited by a variety of factors, including the direct effect of pH (excess H ion concentration) as well as pH-induced toxicities (e.g., Al, Mn) and/or insufficiencies (e.g., Ca, Mg, P, Mo) [3]. An increase in the hydrogen ion concentration of the medium generally causes a decrease in the rate of absorption of cations, probably as a result of competition between the similarly charged ions for binding and carrier sites. Similarly, the role of high pH has often been considered to be detrimental in causing deficient nutrient availability and ionic imbalance.

Depending on the predominant clay-type soil, pH can indicate the percentage base saturation. It also can indicate something about the degree of dissociation of H from cation exchange sites or the extent of H+ formation by hydrolysis of Al. Since the availability of most plant essential elements depends on soil pH, it is an indication of the relative availability of plant nutrients. Thus, soil pH is generally an indicator of both the soil condition and the reactions that occur in the soil.

Soil pH is an important factor influencing the growth of most crops and pastures and the distribution of native plant species [4,5]. Often the effects of pH on the growth of plants are complex and it is difficult to separate the direct effects of excess hydrogen (H+) or hydroxyl (OH-) ions from indirect effects associated with numerous chemical changes in the solubility and availability of various biologically important plant nutrients [6,7].

Among the various plant parts, the roots are directly affected by the pH of the growth medium. Low pH injury or H+ injury is one of the factors responsible for growth retardation in acid soils. Hydrogen ions (H+) increase the solubility of Al, Mn, and Fe in acid soils [8]. The presence of hydrogen ions in the growth medium generally inhibits root elongation, and this phenomenon is observed at extremely low pH [9,10]. It has generally been considered that H+ injury is negligible in a medium at a pH above 4. However, even in this case, the contents of mineral nutrients in plants decrease with the decrease of the pH [11], and, in some cases, mineral ions flow out of the roots [12]. Excess H+ in the growth medium affects plant growth by two processes: (a) Nonspecific inhibition of root elongation, lateral branching, and water absorption; and (b) specific effects on root ion fluxes via H+ competition with base cations for uptake and H+ damage to the ion-selective carrier in root membranes.

It is generally recognized that poor growth in acid soils is not caused by the Ca deficiency of the soils but by other factors such as Al or Mn excess, because plant growth does not improve by the addition of calcium sulfate to the acid soils. In acid soils, it may be difficult to observe the ameliorating effect of Ca, because Al injury is predominant [13]. In solution culture, however, a high Ca concentration in the growth medium alleviates Al injury or low-pH injury [10] and prevents K loss associated with H+ injury [12].

Calcium plays an important role in raising the pH of the growth medium. It is required to sustain cell membrane integrity plus facilitate the active uptake of otherwise competitive cations. This ‘‘Viets’’ effect of Ca can be demonstrated with other polyvalent cations (including Al) [14], and it has been shown to alleviate the toxic effects of high H+ activities. At pH levels of less than 4, H+ may outcompete Ca2+, preventing their absorption, and even displacing Ca present in the root apoplast. Once Ca absorption is repressed, cell membranes lose integrity and the selective ion carrier mechanism dysfunctions resulting in reduced base cation absorption and efflux of cations. Loss of root membrane integrity can also produce the wilting symptoms of low turgor pressure observed with H toxicity.

The important role of Al in acid soil chemistry has been reviewed, as have Al's effects on plant growth in predominantly horticultural and agronomic species. Three general processes by which Al affects plant growth in acid soils are: (a) reduced divalent cation (especially, Ca) uptake by plant roots due to the presence of excess Al in the rhizosphere or the root apoplast; (b) dysfunction of cell division in the root meristematic tissue due to penetration of Al into the root protoplasm and the production of abnormal root morphology; and (c) decreased anion (SO2+ 4, PO3+ 4, Cl-) adsorption by roots due to increased positive adsorption sites in the rhizosphere and root apoplast. Aluminum activity is critical in the above processes because, at low activities, a synergistic response with plant growth can occur. Aluminium is believed to facilitate monovalent cation uptake (especially K uptake via the Viets effect), and increased P sorption, as hydroxy-Al-P-complexes of low positive charge density have been proposed [15].

Several studies have shown that solution pH greatly affects the absorption of inorganic nutrients by plants [4, 5, 16]. Short-term studies have shown that, at low pH, ion transport may be impaired, especially at low Ca concentrations, and sufficient membrane damage may occur to allow the loss of previously absorbed solutes. Similarly, long-term studies on several plant species have shown 53 that prolonged exposure of roots to low pH leads to suppression of lateral root development and, in extreme cases, to death of the root tips [17].

The solubility and plant availability of micronutrient cations in soils generally decreases with increasing pH owing to adsorption-precipitation reactions. The pH of the nutrient solution will affect the availability of certain elements, particularly the micronutrients, stimulating excessive uptake at a low pH, and resulting in removal from the nutrient solution by precipitation at high pH. The pH of the nutrient solution is thought to be best when kept between 6.0 and 6.5, although most nutrient solutions when constituted will have a pH between 5.0 and 6.0. In their experiments, Islam et al. [5] found that tissue concentrations of all essential elements were adequate for healthy plant growth at pH 5.5.

In a solution culture experiment, the concentrations of N, P, K, Ca, Mg, and Mn generally increased in rice leaves with increasing pH values [6] and were higher with NO3-N than with NH4-N, whereas Fe content decreased in rice shoots but increased in roots with high pH. The result suggests that a pH of 5–6 is reasonably good for normal growth and nutrient uptake by rice plants with these N sources.

Nitrogen concentration in plant tops decreased with decreasing pH over the range of 5.5– 3.3, and in tomatoes, the concentrations at pH 3.3–4.0 (1.2 and 1.3%, respectively) were clearly in the deficient range [5]. Nitrogen concentrations in cassava (*Manihot esculenta Crantz*.) tops at pH 3.3 and 4.0 (2.3 and 2.6%, respectively) were also well below the critical N concentration of 5.1% in the fourth and fifth fully expanded leaves of cv. Llanera [18] and the normal N concentrations range from 4.5 to 6.5% in young fully opened leaves. No satisfactory explanation can be given for the decline in plant N concentrations at low pH. Bassioni [19] observed that NO3- uptake by excised barley roots was less at pH 4 than at pH 6. However, this result is somewhat suspicious, as the test solution did not contain Ca. Rao and Rains [20] reported higher rates of NO3 absorption in short-term uptake experiments with barley roots at pH 4.0 than at pH 5.7 or 8.5. Similarly, in a flowing solution culture experiment, Forno [21] found that mean rates of N uptake by cassava (as NO3) per unit root weight were either higher at pH 4.4 than at pH 6.8 (*Cassava cv. M. Aus. 3*) or approximately the same (*Cassava cvs. Nina and Ceiba*). In the roots of sunflower (*Helianthus annuus* L.) and flax, the total N concentrations were strongly reduced at pH 4 [22]. In soils with pH 7 or below, high concentrations of NH4+ can be toxic to raddish (*Raphanus sativus* L.) [23], and NH4+ toxicity is particularly deleterious to young seedlings, limiting plant yields.

Ammonium absorption by plants can rapidly depress solution pH to injurious levels in noncalcareous soils (NH4+ and Al3- toxicities) because NH4NO3 contributes to soil acidity. Ammonium toxicity occurs in many plant species, but it is not considered a problem when the plants are grown in calcareous soils (free CaCO3). Barker and Mills [24] noted that even when all of the N is ammonical, near-normal growth can be obtained if the pH of the medium is buffered to near neutrality (e.g., calcareous soil). Less N plant tissue was found at pH 5.5 under all redox potential conditions in the soil, with the highest pH being 7.5 [25].

Nitrification of NH4-N-based N fertilizers is known to increase soil acidity. Legumes increase soil acidity because they absorb more cations than anions from soil [26]. Nitrogen, in the NO3 form, seems almost universally to lead to an increase in pH. The observed effect of pH on NO3 uptake suggests that both H+ and OH- are involved in the absorption process. At low pH values, H+ may cause injury to the root tissue, whereas at higher pH values, competition with OH- reduces NO3- uptake.

Breemen *et al.* [27] have indicated that nitrification of NH4+ and accompanying soil acidification can occur even at a pH of less than 4. Lowering of pH is associated with the uptake of N as NH4+ [28]. The Uptake of NH4+ by the roots results in a release of H+. The rhizosphere (or nutrient solution) becomes acidified and root integrity is impaired. This type of NH4 + toxicity can be avoided by pH control of the rooting medium. In their experiment with Kentucky bluegrass (*Poa pratensis* L.) and using N sources, Davis and Dernoeden [29] observed that soil pH was affected by N sources. In the years 1987 and 1988, the NaNO3-treated plots had the highest pH, whereas SCU- (sulfur-coated urea) and NH4Cl-treated plots had the lowest pH. Acidification was greatest(pH 5.3) in NH4Cl-treated turf, whereas pH was highest (pH 6.0) in plots subjected to NaCl. They further stated that NH4Cl-treated plots generally exhibited severe disease injury. Sodium nitrate-treated plots which had the highest soil pH were associated with more disease injury when compared with SCU-treated turf. The data provide no clear evidence for a relationship between disease and soil reaction as influenced by the N sources.

The concentration of H+ in the growth medium has an especially important effect on phosphate absorption, because over the physiological range of pH values, the predominant ionic form shifts from univalent (H2PO4+) to bivalent (HPO4+), and finally to trivalent (PO4+) as the medium becomes more alkaline.

Decreases in the rate of phosphate absorption with increasing pH are well documented [30]. Arnon and Johnson [10] considered that P deficiency contributed to the poor growth of their plants at higher pH values. However, Islam *et al.* [5] reported that tissue phosphate concentrations were adequate in their plants at pH 8.5. Khalid *et al.* [31] reported that the availability rates of P depended on the differential sorption under the influences of changing pH. The increase in pH of the test solution from 5.3 to 7.4 may increase P absorption. Arnon *et al.* [11] found that for tomatoes, maximum absorption of P occurred at pH 7 and decreased toward pH 3 and 9. Ponnamperuma [32] reported that the increase in pH of acid soils due to submergence is beneficial to plants, as it increases the P availability.

The shifting of pH from acidity to neutrality increases the P mineralization. Several essential elements become limiting to plant growth at alkaline soil pH. For example, the availability of phosphate, Fe, B, Zn, and Mn has been shown to decrease at high pH. Precipitation of phosphate by Ca and the cations by carbonate, hydroxide, or phosphate is responsible for decreased availability of these elements. Hagen and Hopkins [30] observed that excised barley roots absorbed both univalent and bivalent phosphate from the growth medium. This may be because roots absorbing more anions than cations excrete OH- rather than H+, leading to an increase in solution pH [33].

Soil pH can indirectly reflect the P distribution pattern of soils to a certain degree but not perfectly. The pH of the soil solution determines the form of P absorbed by plants, however, P is absorbed mainly as the inorganic dihydrogen ion (H2PO4 +). It is known that Ca-P is found in large amounts in alkaline soils, and Al-P and Fe-P are found in acidic soils. Therefore, the concentration of phosphorus in the soil solution depends mainly on soil pH, and a decrease in pH can reduce P concentration by causing the precipitation of Al-phosphate or Fe-phosphate as amorphous polynuclear complexes with high surface area.

The addition of NH4+ rather than NO3- increases P uptake from the neutral soils [28]. Generally, absorption of the NH4+ tends to lower the pH in the rhizosphere, and in the soil studies, there was a corresponding increase in the concentration of phosphate in the solution. At 1 mM NaNO3 and lower pH [4], the ion uptake (N, P, K, and S) and growth of wheat and rice were severely affected [34]. There was a great decrease in the P concentration with the increase in CaCO3, which was mostly due to the transformation of available P to di- and tricalcium phosphates and also to apatites owing to the formation of ferric phosphate/hydroxy phosphate.

Decreases in the K content of plants were observed under low pH conditions [12], and the movement of K in roots was symplastic. It is assumed that in the plants which exhibit a low K content in a medium with a low pH, the function of the plasma membrane is impeded by H+. One of the main physiological roles of K is to maintain the osmotic pressure of cells (maintenance of turgor). As the roots elongate rapidly by the successive production and thickening of new cells, they must absorb a large amount of K to maintain the K concentration of these newly formed cells at a suitable level [7]. Therefore, it is assumed that H+ decreases the function of the plasma membrane and promotes K loss or the inhibition of K uptake, and consequently brings about poor root growth.

Potassium loss associated with a low pH can be alleviated by the increased Ca concentration in the growth medium [12]. In gramineous crops, the index of the K content tended to increase with the increase of the Ca concentration in the medium. Many experimental results have been published on the stimulation of K absorption by Ca in plant roots [35].

Large decreases in the rate of absorption of Ca with decreasing pH have been reported. The availability of Ca has been limited at low pH; this is because as the amount of H+ increases, the amount of Ca decreases. A strong antagonism between H+ and Ca2+ in legume nodulation has been documented [36], and calcium accumulation in maize has been associated with soil pH. In their experiments, Inoue *et al.* [7] observed that under both conditions of low pH and low Ca concentration, the Ca uptake was strongly inhibited by H+, and consequently the corn shoots suffered Ca deficiency, leading secondarily to poor root growth of several gramineous crops. This inhibition of Ca uptake appears to be caused by the antagonism between H+ and Ca2+ at the position of the substitution radical of the cell wall and/or of the plasma membrane. Both the contents of K and Ca in barley, wheat, and rye were low in medium with a low pH. It is, thus, considered that since the functions of the plasma membrane and Ca uptake were inhibited by H+, the root growth was considered poor. The roots of gramineous crops generally display a low ability to absorb Ca and transfer Ca to the top. Calcium plays an important role in the strengthening or maintenance of the cell wall and plasma membrane. Assuming that H+ and Ca2+ antagonize each other at the position of the substitution radical of the cell wall or plasma membrane, the increase of the Ca concentration in the medium may alleviate the H+ injury.

Calcium concentrations in maize at pH 3.3 and 4.0 (0.39 and 0.37%, respectively) were below the concentration normally considered adequate for healthy growth [5]. However, Loneragan and Snowball [37] obtained the maximum yield of young maize plants in flowing solution culture when the Ca concentration in the tops was only 0.12%. In the same experiment, tomato and wheat cultivars Gabo and Wongoondy achieved maximum yield, with Ca concentrations in the plant tops of 1.29, 0.15, and 0.32%, respectively. These Ca concentrations are well below those obtained in the tops of tomato and wheat *cv. Gatcher* in the experiment carried out by Islam *et al.* [5] at low pH with different plant species.

Arnon and Johnson [10] attributed much of their growth reduction below pH 5 to inadequate Ca absorption. In a subsidiary experiment with lettuce (*Lactuca sativa* L.) and tomato, these investigators showed that raising the initial Ca concentration in the nutrient solution from 2000 to 7000 µM increased yields at both pH 4 and 5, whereas lowering the initial Ca concentration to 500 µM lowered plant yields. Further evidence of the interaction between the effects of low pH and Ca concentration comes from studies in legume nutrition. Lucerne (*Medicago sativa* L.) plants supplied with combined N grew equally well at pH 4 and 5, with a Ca concentration of 5000 µM, but that growth was poorer at pH 4 when lower Ca concentrations were used.

In an unsuitable environment, limitation in Ca supply to the plant roots caused a disturbance in the growth and metabolic processes in plants. The deficiency of Ca reduces the absorption and accumulation of monovalent cations and increases the uptake of divalent cations [38]. Accumulation of P, K, and Na decreases in all parts of Ca-deficient potato plants. This view strengthens the argument that the absence of Ca in the growth medium will cause a decrease in the uptake of K and Na and increases in the accumulation of Mg in plants. Calcium deficiency causes the accumulation of oxalic acid in such a quantity as to become injurious to plants. Calcium helps in the precipitation of oxalic acid and soluble oxalates in the form of Ca-oxalate and protects plants from being affected by more H+ concentrations. Large decreases in the rate of Mg absorption by different crop plants have been reported with decreasing pH [11]. Magnesium concentrations in the tops of plant species at pH 3.3 and 4.0 (0.03–0.16%) were sufficiently low to be either deficient or marginally limiting for plant growth [6].

The solubility of Fe salts in soils is reported to be governed by the pH of the system, which affects the availability of Fe to the plants. The increase in pH of acid soils is due mainly to the reduction of ferric-Fe to ferrous-Fe. The decrease in pH of sodic and calcareous soils and the check on the pH rise of acid soils are the results of the accumulation of CO2, soil reduction, and organic acid production. Increased Fe availability on calcareous soils can also be achieved by lowering the pH of the bulk soil with the application of S and sulfuric acid. In a short-term experiment, increasing the solution pH from 3.5 to 8.5 decreased the concentration of Fe on the tops of rice plants, whereas, in roots, the Fe content increased [4]. At a high-solution pH, the new leaves become chlorotic. The appearance of Fe deficiency in rice plants at high pH may be explained by the low solubility of Fe in the rooting medium by the fast oxidation of ferrous Fe and by immobilization in the roots. The action of rice roots in oxidizing Fe2+ to Fe3+ is believed to be responsible for the oxidation of H2S by the roots, suggesting that chlorosis at high pH may be related to the more rapid oxidation of ferrous Fe to higher forms [9].

When the pH of the growth medium is high, Fe phosphate is precipitated in the stem and both high phosphate and increased pH are known to enhance Fe chlorosis. High levels of P and Al in the growth medium often have been found to reduce Fe absorption and utilization, especially under neutral or alkaline conditions [13]. Rice plants are given excess P in the growth medium and progressively accumulated Fe [39]. The activity of iron is affected by P in the plant tissue or nutrient media. Poor Fe nutrition depressed the growth of maize and wheat at pH 7.5 and 8.5 despite the use of Fe N, N-dihydroxyethylethylene-diamineacetic acid (HEDDA) (Sequestrene 138) as a Fe source. This compound is reported to be stable over the pH range of 4–9 [40]. Iron concentration in the tops of maize grown at pH 8.5 (85 µg/g) is in the range that has been considered deficient for this species. This observation is confirmed by the development of severe symptoms of Fe chlorosis [41].

The high hydroxyl and bicarbonate ion concentrations associated with the alkaline soil solution in a calcareous soil keep available Fe2+ concentrations too low to supply sufficient Fe for normal plant uptake. Similarly, bicarbonate induced Fe stress for plants grown in nutrient solutions and in alkaline soils. Some studies have indicated a combination of bicarbonate and high P-induced Fe chlorosis. Iron chlorosis is also enhanced under conditions of increased soil moisture and a high Fe-to-P ratio.

When large amounts of NO3- are taken up, more hydroxyl ions are released by roots resulting in decreased availability of soil Fe [42]. The availability of Fe, Mn, Zn, and Cu was low in calcareous soils and added P antagonized micronutrient deficiencies more under high pH conditions. Therefore, under conditions where Fe is highly insoluble and immobile, the main mechanism of Fe uptake may be by direct contact between insoluble Fe compounds and plant roots. Inhibition of lateral root development would have detrimental effects on the ability of the roots to reduce Fe2+ since the iron-reducing activity occurs at or near the surface of young lateral roots.

Soil pH is often the determining factor in whether the soil will respond to Mn fertilization. Liming coastal plain soils from pH 6.0 to 6.5 intensified Mn deficiency symptoms in soybeans [43,44]. Fitts *et al.* [45] observed yield responses to Mn only where the soil pH was neutral or alkaline. These investigators found that liming above pH 6 reduced the leaching of Mn and decreased plant Mn. The decrease in soil pH from 6.8 to 6.0 during a greenhouse experiment prevented Mn deficiencies from developing in soybeans. Jones and Nelson [46] reported that liming soils to a pH of 5.5 or above reduced extractable soil Mn, decreased foliar Mn concentration, eliminated toxic effects, and increased soybean yields. Manganese availability is inversely related to soil pH and its oxidation-reduction potential. Plants take up the divalent form of Mn for their normal growth. The oxidation of divalent Mn to less soluble forms occurs in the pH range of 7–8, primarily as a result of microbial activity. At soil pH less than 7, Mn was sufficiently available for normal turf appearance and growth of Bermuda grass (*Cynodon dactylon* L.), and Mn deficiencies observed were pH induced rather than attributable to insufficient total Mn in the soil [43]. A soil pH of 5.3 resulted in the highest concentration of Mn in the soybean leaf, whereas a pH of 7.0 showed the lowest Mn concentration in the leaf [47]. The higher concentration of Mn in the leaf tissue at pH 5.3 was due to the greater solubility of Mn under the strongly acid solution of the soil and consequently absorption by the soybean.

With decreasing pH, the concentration of Mn decreased in crop plants. Similarly, decreasing the solution pH from 7.0 to 5.4 resulted in decreased Mn concentration in the tops of two Medicago species. Apparently, in the poorly buffered solution, high Ca levels ameliorated the adverse effects of an acidic pH on Mn uptake. Manganese concentrations in tops of maize (*Zea mays* L.) plants at pH 3.3 and 4.0 (12 and 14 µg/g, respectively) decreased [5] and were in the range that is considered to be inadequate for healthy growth.

Zinc deficiency is prevalent in acid, leached sandy soils having a low Zn content and in neutral and alkaline soils having high levels of available P and organic matter. The availability of Zn in soils may become critical at soil pH values as low as 5.3. Zinc uptake by corn was significantly correlated with soil pH between 4.3 and 7.5. Lime reduced Zn uptake by red clover (*Trifolium pratense* L.), timothy, and bromegrass (*Bromus marginatus* L.). The N fertilizers affect the availability of Zn, and these effects were attributed to changes in soil pH, and NaNO3 decreased the Zn uptake and (NH4)2SO4 increased it [48]. Severe Zn deficiency in subterranean clover with increasing N supply is due to the formation of a Zn-protein complex in the roots. The addition of CaCO3 generally decreased the Zn content of sorghum at soil pH levels between 5.7 and 6.6 [49]. The reduction in Zn uptake induced by CaCO3 was attributed to the increased soil pH and not the Ca added. Similarly, the addition of lime to sandy Alabama soils to a pH near 6.5 produced Zn deficiency in corn.

Reducing the pH of the test solution from 5.5 to 4.5 decreased Zn absorption rates by factors of 1000 and 10,000 in the rice cultivars IR6 and Basmati-370 [50]. Similarly, reducing the solution pH from 5 to 3 reduced zinc absorption by a factor of about 100 in wheat seedlings [51]. Zinc absorption by plants usually decreases as the concentration of H+ increases, presumably because of the direct effect of H+ toxicity and because of an indirect effect of competition between Zn2+ and H+ ions from uptake sites on the root surface. At low pH in the presence of citrate (pH 4.0 and 4.6), when the toxicity effect of H+ ions was greatest, the roots did not respond to an increasing concentration of Zn [52]. Soil pH, organic matter content, and the presence of other cations affect the availability of Cu to plants in soils. At a pH value above 4.7, Cu is probably precipitated as Cu(OH)2 in the presence of organic matter. Increasing the soil pH decreases the solubility and availability of Cu to plants [53]. However, the pH at which Cu availability is highest appears to vary with the organic matter content and the presence of other ions.

The chemistry of boron (B) in the soil is still poorly understood. It is probably present in the soil solution as boric acid, B(OH)3. Liming acid soils to a pH of 7 and above have often resulted in B deficiencies. The fixation of applied B in soils was much greater at pH 7 and above. The work of Sims and Bingham [54] indicates that hydroxy Al and Fe materials are responsible for B fixation when acid soils are limed. Retention of B by hydroxy Al and Fe compounds was pH dependent. According to Sims and Bingham [55], retention of B was maximum at pH 7 with hydroxy Al compounds and at pH 8.5 with hydroxy Fe compounds. These investigators postulated that the retention of B is due to anion exchange reactions in which borate ions replace hydroxyl ions.

Soil pH also affected the availability of water-soluble B. As the pH increased from 5.2 or 6.3 to 7.4, the concentration of B in the plant decreased [56]. Boron absorption by plants decreased much more when both pH and Ca concentrations were increased. The uptake of B has been shown to decrease as the Ca uptake has increased. Availability and plant uptake of native or added B were generally lower in calcareous soils than in noncalcareous soils. A high pH and high Ca concentrations of the nutrient solution decreased B uptake by cotton. Neither high pH nor high Ca alone had any effect on the absorption rate of B. It was suggested that the presence of a high concentration of Ca2+ and OH- affected the B adsorption mechanism. Therefore, pH appeared to have a physiological effect on B absorption by plants when the supply of Ca was high.

The S requirements of crops are very similar to their P requirements. Sulfur deficiency is most widely found in leguminous crops. The atmosphere contains S compounds, partly as aerosols and partly as gaseous SO2. In an experiment, Kamprath *et al.* [57] observed that there was a marked decrease in the amount of sulfate adsorbed when the pH of the soil was increased from 5 to 6. The effects of pH on sulfate adsorption were much more pronounced on soils that contained appreciable amounts of Al oxides and hydrous Fe. Chang and Thomas [58] have suggested that sulfate adsorption increases when the pH is lowered because the replaced hydroxyl ions are more effectively neutralized by H+ resulting from the hydrolysis of Al replaced by the cations added with the sulfate in the soil. The adsorption of sulfate was greater from a solution of CaSO4 than from K2SO4. However, the soil pH had a greater effect on sulfate adsorption than did the nature of the cation.

It is well known that acid soils and those rich in Fe stone can strongly fix Mo. In a review of factors affecting the availability of Mo, Davis [59] stated that many investigators have shown that Mo availability increases as the pH of the acid soil is increased. Stephens and Oertel [60] suggested that this might be due to hydroxyl ions replacing adsorbed molybdate ions. The amount of Mo sorbed by soils and the amount of hydrous oxides increased as the pH decreased. Molybdate ions replaced surface hydroxyls of hydrous oxides of Fe and Al in acid soils. Water-soluble Mo increased sixfold as the pH increased from 4.7 to 7.5. Generally, the replacement of tightly adsorbed Mo by OH- ions is responsible for the increase in water-soluble Mo as the pH is increased.

**CONCLUSIONS**

As natural stress, soil pH has far-reaching effects on the growth and nutrient uptake by crop plants. It is difficult to minimize the abnormal effects of pH exerting on the growth of crop plants. However, efforts should be made to reduce the ill effects of pH to maintain the normal growth of plants in a growing medium.

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