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Effect of Soil Acidity on Nutrient Availability and Phytohormonal Responses: A Review

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Abstract
More than half (52%) of all fertile and productive soils worldwide are currently considered to be degraded by various factors. Among those factors, soil acidification is a very important issue. About 70% of the potential arable land and 30 % of the total land area experience some degree of soil acidity. There are several reasons why soil becomes acidic, but rainfall and leaching, acidic parent material, harvesting of high yielding crops, improper nitrogen fertilizer application, and organic matter decays are the principal ones. Acid soil affects plant growth, development and production in a number of ways. In one way, it reduces plant productivity by introducing several toxicities like Al^{3+}, Mn^{2+}, and H^{+} and in another way it affects nutrient availability primarily by altering the form of nutrients in the soil. Major plant nutrients including N, P, K, S, Ca, and Mg, and trace elements like Mo are less readily available in it and may be insufficient to support plant growth and development. Not only plants the functioning of soil microbes is also impaired by acidic conditions. Most microbial functions, such as the decomposition of organic matter and the cycling of nutrients are reduced in it. As a result, it greatly reduces the pace at which nutrients are mineralized by soil microbes into plant-available forms, potentially reducing plant absorption. Significantly, it can prevent the establishment of symbiosis and legume nodulation. Plants attempted to withstand all the effects of acid soil by exhibiting a variety of morphological and physiological responses. Mainly they tried to acclimate and adapt by altering the biosynthesis and action of phytohormones.
Keywords: acid soil; nutrient availability; effects of acid soils; phytohormones
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1. Introduction

Both the availability and the quality of food are heavily influenced by agriculture. Seventy to eighty percent of people in developing nations rely on it as their primary source of income and livelihood (Oliver and Gregory, 2015). Over 80 million people are added to the world's population each year, which will put tremendous demands on the existing agricultural resources and increase pressure to exploit any remaining lands with agricultural potential (IAEA, 2000). The amount of food produced is anticipated to rise in order to adequately feed the projected global population of 9.3 billion by 2050 (UN, 2015; Rojas et al., 2016). However, 70% of the potential arable land and nearly 3,950 million ha, or 30%, of the overall land area, experience some degree of soil acidity (Von Uexküll and Mutert, 1995). Of the 3.01 billion ha of land in Africa, 659 million ha, or 22%, have acidic soil (Malcolm and Andrew, 2003). Almost 41% of Ethiopia's entire land area is acidic (Schelede, 1989).

Soil is one of the natural resources vital for the continuation of life on earth. Living organisms depend on them, which in turn are dependent on the organisms that make up the soil (Brady and Weil, 2002). They must be conserved, improved, and protected. Under natural conditions, plants obtain all the essential nutrients they need for growth and development from it. They can absorb nutrients through their roots and the mycorrhizal association that has developed in the rhizosphere. Moreover, its environment influences root uptake and anchorage capacity. The ability of the roots to absorb mineral nutrition will be supported by them that have all the available and appropriate mineral nutrients, sufficient organic matter, and good drainage capacity. On the other hand, roots' capability to absorb mineral nutrition and sustain plant growth will be reduced in them with low pH, less nutrient availability, more soluble toxic metal ions, less organic matter, and poor drainage capacity. The fixation and availability of its nutrients are substantially affected by pH levels, particularly low ones. Abundant acidic cations in the colloidal soil solution of the system are toxic to crop growth and can lead to reduced yields (Zheng, 2010).

Over half (52%) of all fertile and productive soils worldwide are currently considered to be degraded or severely degraded (UNCCD, 2015). Soil acidification, nutrient depletion, soil erosion, and soil chemical imbalances may lead to crop failures and malnutrition, reducing the quality and quantity of food available to alarmingly rising population (Kopittke *et al.,* 2019). Among these soil degrading factors, soil acidification is a very important issue.

According to Yang et al., (2004), more than half of the world's population currently resides in areas dominated by acid soils, where productivity is declining and it is difficult to feed the world's expanding population, particularly in the tropics (Hartemink, 2002). Soil acidity is a significant yield-limiting factor particularly, in many developing nations where food production is a critical issue (Kochian *et al.,* 2015). In Africa, due to lack of N through leaching, fixation of phosphorous, and lack of soil organic matter, it is a major constraint of agricultural productivity (Opala *et al.,* 2015).

Most acidic soils are found in tropical and subtropical regions of the world. The leaching of basic cations like K^+, Mg^{2+} and Ca^{2+} in tropical soils over millennia has been replaced by the release of H^+, Al^{3+}, and Mn^{2+} cations, which contribute to acid-related stressors on crop production (Okalebo *et al.,* 2009). Due to a lack of essential mineral nutrients, acid infertility factors restrict crop growth, yield, and soil productivity in heavily weathered soils of humid and sub-humid areas (Akinrinade *et al.,* 2006).

Acidic soil reduces crop productivity, especially if acid-producing fertilizers such as DAP or ammonium sulfate are applied constantly for many years (Nekesa, 2007). As the soil suffered from deficiencies of several nutrients, the application of chemical fertilizers became mandatory to boost agricultural yields. However, mineral fertilizers are often scarce and expensive in developing nations and their nutrient contents are usually limited to two or three elements. So, their application could result in an imbalance of nutrients and aggravate the problem of soil acidity (Nottidge *et al.,* 2006). Constant cultivation, coupled with the use of unbalanced nutrition and the wrong type of fertilizer, has increased chemical degradation on arable lands, reducing the potential of the soils to support crop growth (Nandwa, 2003; Mugendi *et al.,* 2007). Due to toxic amounts of aluminum (Al) and the concurrent phosphorus (P) deficit that inhibits plant growth, continuous cultivation with the use of inorganic fertilizer has resulted in the development of soil acidity (Kisinyo *et al.,* 2005).

Soil acidity retards plant growth and declines productivity in many ways. The impacts are caused by a lack of essential nutrients including P, Ca, Mg, and Mo as well as the toxicity of Al, Mn, or H ions Acid soils frequently have N and possibly B deficiencies due to their highly leached nature. Moreover, there is a significant reduction in the availability and uptake of nutrients by plant roots as well as the decomposition of organic matter and nutrient recycling by soil microorganisms (Edmeades *et al.,* 1995). However, toxicities are one of the most frequently identified causes of yield loss. The primary yield limiting factors are the Al and Mn toxicities (Kochian, 1995; Raman *et al.,* 2002; Tang *et al.,* 2002). In general, soil acidity and other related factors account for 25 to 80% of yield losses in a variety of crops (Herrero-Estrella, 2003). Although many crops in agroecosystems suffer from stunted growth and reduced yield due to acid soils, plants attempt to withstand the impacts of soil acidity primarily by developing suitable hormonal responses. Its effect on nutrient availability and phytohormonal responses of plants has not yet been properly compiled. Thus, this review is conducted to fill the gap.

In general, the main purpose of this paper is to assess the effects of soil acidity on plant nutrient availability and phytohormonal responses to acid soils.

2. The chemistry of soil acidity

2.1 Soil acidification processes

Soil is made up of various components that determine its properties. These include organic matter (living and dead), mineral particles (sand, silt and clay), air, and water. So, soil acid chemistry is very complex. According to Bolan et al., (1991), agricultural practices can also accelerate the continuing process of soil acidity. Soil acidification is primary caused by the release of protons (H^+) during the conversion and cycling of C, N and S in the soil-plant interfaces (Ulrich and Summer, 1991). So, when soils are unable to act as a buffer against P^H decline, inputs of H^+ as well as changes in soil C, N, and S might have adverse effects (Mason et al., 1994). In the N and S cycles, H^+ is produced by the mineralization and oxidation processes of organic N and S. It is balanced by OH^- through uptake and assimilation of NO_3^- and SO_4^{2-} by plants and microbes (Veries and Breeuwasma, 1987). Permanent acidity is left in the soil when NO_3^- and SO_4^{2-} are leached with charge-balancing basic cations (Ca^{2+}, Mg^{2+}, Na^+ or K^+) as opposed to the H^+ produced during oxidation. This is observed in soils with reduced P^H and low P^H buffering capacity (Breemen, 1991).

Other processes that lead to permanent soil acidification are organic N accumulation and nitrification of NH_4^+ based fertilizers. When plants uptake and assimilate NH_4^+ or N, H^+ ions are released into the rhizosphere. Due to the buildup of organic N in the rhizosphere soil, the expelled H^+ ions are then separated from it and transferred to bulk soil. The decarboxylation of organic acid anions leads to the accumulation of organic N in the rhizosphere soil. Accumulation of more soil organic nitrogen in the rhizosphere increases acidity by lowering the bulk soil pH (Williams, 1980). Similarly, N loss through NH3 volatilization or denitrification causes permanent soil acidification only when N is provided in the form of ammonium-based fertilizers (Bolan and Hedley, 2003).

2.2 Soil P^H ranges

Soil acidity is identified by measuring soil reaction using P^H. The term P^H describes the potential or power (P) of the hydrogen ion (H^+) concentration in water. Soil P^H can be measured in the field with a test kit or for more accurate findings, a sample can be sent to a soil lab.

The range of the P^H scale is 0 to 14. While $P^H = 7$ is neutral (neither acid nor base), $P^H < 7$ is acidic, and $P^H > 7$ is basic (alkaline). The negative logarithm of a soil's H^+ concentration, or PH, is actually a way to express the amount of hydrogen ions in solution using an electrical potential. One P^H unit corresponds to a 10-fold change in acidity. So, a soil with a P^H of 5 is 10 times more acidic than a soil with a P^H of 6 and 100 times more acidic than a soil with a P^H of 7. Soils are categorized into a number of acidity or alkalinity classes depending on their relative degree of acidity (Brady and Weil, 2002) as shown in figure 1.

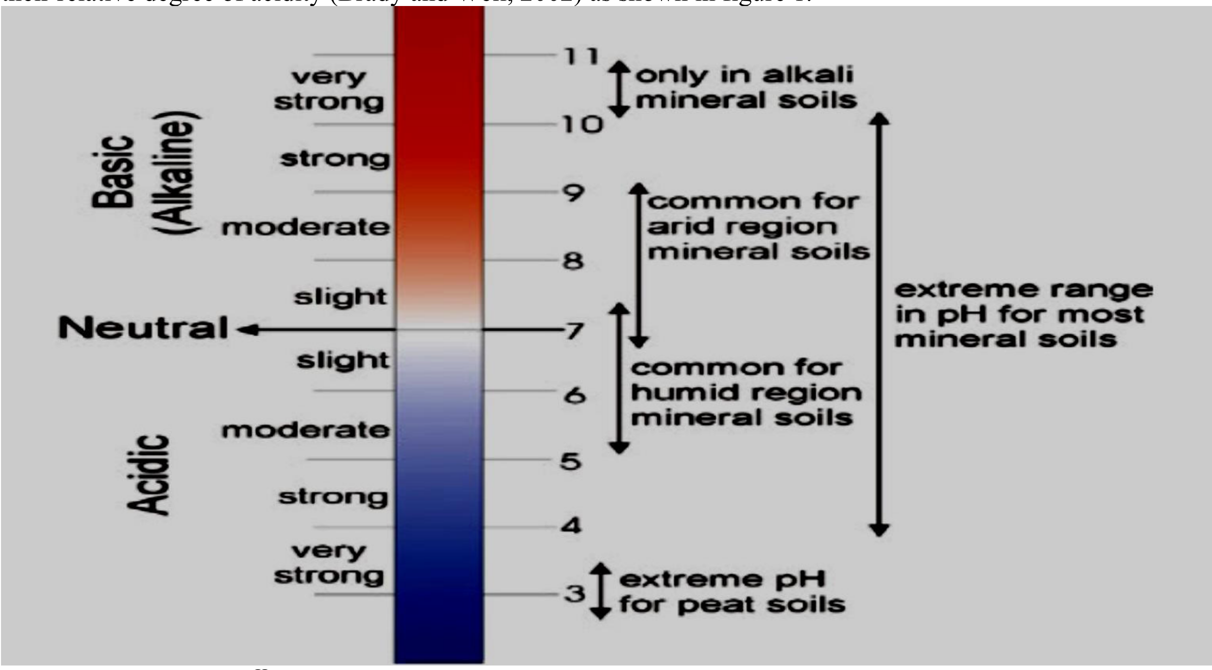

Figure 1. General soil P^H ranges and reaction classes of soils (Source: Brady, 1980).

Soil pH is a measure of the activity of hydrogen ions (H+) in soil solutions. It lowers as H^+ activity increases. Most desirable crop nutrients become less available when the soil P^H decreases, while others, often undesirable ones, become more accessible and may even reach to toxic levels (Ristow et al., 2010).

An acid soil is the one that has a P^H value below 7.0. This includes strongly acid soils with P^H value below 5.0 and moderately acid soils with P^H between 5.0 and 6.5 (Brady and Weil, 1996). The ideal soil P^H lies between 6 and 6.5 because nearly all of the nutrients needed by plants are present in optimal amounts in these P^H ranges. If a soil P^H test shows that the soil has a P^H below 6.5, it is usually recommended to use crushed limestone. Lime stone contains Ca in addition to having the capacity to enhance soil P^H. Dolomitic lime stone is preferred by some because it contains both Ca and Mg, however, soils with high Mg content (serpentine) do not need more Mg. Acid soils (P^H <7) are common in humid regions. In these soils, the concentration of H^+ exceeds that of OH^-. Most plants grow best in slightly acidic soil. Soils with P^H <6 are more likely be deficient in some of the available nutrients for optimal plant growth. They are especially deficient in Ca, Mg, and K. In strongly and very strongly acid soils Al^{3+}, Mn^{2+}, and Fe^{3+} can occur in toxic amounts due to their high solubility. In addition, these ions will react with phosphates (primary and secondary orthophosphates) to form insoluble phosphates in phosphate retention and fixation (Kim, 2010).

The only way to determine the acidity of soil is to sample it and measure its P^H. Samples of the topsoil and subsurface soils should be taken for P^H analysis. Because the P^H of topsoil and subsurface soil can be quite different and sampling only the topsoil may lead to erroneous conclusion like recommending inadequate lime application. Because of this, subsurface acidity cannot be identified or estimated using simply top soil P^H. To determine the specified soil P^H profile, samples should be taken at depths of 0–10cm, 10–20cm and 20–30 cm (Chris and Stephen, 2009).

2.3 Major Causes of soil acidity

A number of anthropogenic and natural factors contribute to the progressive process of soil acidity (Rahman et al., 2018).These factors are involved in the formation and acceleration of soil acidity. Some agricultural practices speed up the natural rate of soil acidity. Inappropriate use of nitrogen fertilizers, particularly those containing ammonium, crop rotations that boost the likelihood of leaching, excessive irrigation that increases leaching, increased removal of basic cations from harvested products, and increased N-fixation by legumes as a result of fertilizer nutrient application are a few examples of such practices.

Moreover, industrial activities, acid rain, and ammonia volatilization from pastures and field crops in industrialized nations all contribute to increased soil acidification (Kennedy, 1992). There are several reasons why soil becomes acidic, but the main ones that directly affect how acidic soil forms are rainfall and leaching, acidic parent material, harvesting of high yielding crops, improper nitrogen fertilizer application, and organic matter decays (Gordon, 2004; Negash Teshome, 2017; Getachew Agegnehu et al., 2019). The above causes are more readily comprehended by comparing the abundance of acidic cations like H^+ and Al^{3+} with that of the alkaline cations like Ca^{2+}, Mg^{2+}, K^+, and Na^+ (Jackson, 1967). This is due to the fact that cation exchange activities generate a net loss of basic cations from the soil profile, which leads to soil acidification.

2.3.1 Rainfall and leaching

Excessive rainfall is a powerful agent for removing basic cations from the soil profiles over a long period of time. It accelerates soil acid formation by leaching the basic soil cations such as Mg^{+2}, Ca^{+2}, K^+ and Na^+ from the soil profile and leaving acid forming cations like H^+, Al^{+3} and Fe^{+3} in the soils. This occurs when the rainfall surpasses the evapo-transpiration processes in most of the rainy seasons. At this condition, the basic soil cations (Mg^{+2}, Ca^{+2}, K^+ and Na^+) are gradually depleted and replaced by the acid forming soil cations (H^+, Al^{+3} and Fe^{+3}) that are held in the colloidal soil reserves. Therefore, soil acidity is the problem of excessive rainfall (Slattery and Hollier, 2002).

The acidification process is accelerated in humid environments where a lot of rainwater rapidly percolates into the soil profile. Sandy soils are frequently the first soil type to become acidic due to their rapid water percolation ability, lower buffering capacity (contain only little reservoir of bases), and low clay and organic matter contents (Jonathan and Paul, 2007; Michael, 2014). Conversely, the retention and availability of fertilizer's cations and anions in acid soils are impacted by clay soils because of Fe and hydroxyl Al holding potentials. The effect of precipitation on the development of acid soils is so slow that it can take hundreds of years for the parent material to become acidic during heavey rain fall (Jackson, 1967).

2.3.2 Acidic parent materials

As it is known soil is formed from the parent rock by gradual weathering processes. Based on the chemical composition of the parent materials, soils will gradually turn acidic or basic.

Therefore, the chemical makeup of the parent material has a role in determining the acidity of soil. This means that soils created from basic parent rocks or alkaline parent materials have a higher PH than soils formed from acidic parent rocks. In contrast to soils created from calcareous shale or limestone, soils derived from granite rocks are likely to be more acidic (Jackson, 1967; Messrs and Brahy, 2002; Spies and Harms, 2007).

In general, weathering can result in the mineralization of acidic soil parent materials like gibbsite [Al $(OH)_3$], an aluminium hydroxide mineral of the oxides and hydroxides group, and goethite [α-FeO(OH)], a common iron oxide mineral, which releases protons (H^+) and contributes to soil acidity.

$$Al(OH)_3 + 3H^+ \rightleftarrows Al^{3+} + 3H_2O$$

$$Fe^{3+} + 6H_2O \rightleftarrows Fe(OH)_3 + 3H^+ + 3H_2O$$

2.3.3 Crop production and nutrient removal

One of the most important factors in the process of soil acidity is the ongoing harvesting of productive crops like wheat. To meet their nutritional needs, these crops actively absorb the basic cations (Ca^{+2}, Mg^{+2}, and K^+) through their roots. When these crops are continuously harvested and removed from the field, the basic cations that play a role in counteracting soil acidification are lost over time, making the soil in the field acidic. If the whole crops or plants were allowed to die naturally, all parts returned to the soil and its P^H would not change much. This is so because leaves and stems contain more fundamental components than grain does. However, less alkalinity is restored to the soil and the land becomes more acidic when all plant components are harvested for food and forage. Similar to high yielding crops, high producing forages like Bermuda grass or alfalfa can accelerate the development of soil acidity (Spies and Harms, 2007; USDA, 2011).

Constant harvesting of crops can cause soil acidity not only by uptake of soil basic cations, but also by release of H^+ from the roots into the soil (Misganew andualem, 2021). They do this to correct the imbalances brought on by the loss of positively charged ions from the soil solution.

2.3.4 Decomposition of Organic matter

Although organic matter in the soil has numerous positive impacts, an increase in organic matter can make the soil more acidic. The release of H+ from decaying organic matter is what lowers the PH of the soil. In addition, weak carbonic acid (H_2CO_3) is created when the CO2 produced during the decomposition process reacts quickly with water, which might increase the acidity of the soil (Slatter and Hollier, 2002). This is the same acid that develops when CO_2 in the atmosphere reacts with raindrops to naturally form acid rain.

$$RCH_2OH + O_2 + H_2O \longrightarrow RCOOH \longleftrightarrow RCOO^- + H^+$$

The decomposition of organic matter releases numerous other weak organic acids in addition to carbonic acid. In principle, the contribution of organic matter decomposition to the development of acidic soils is very small, and it would be the cumulative impacts over a number of years that might be evaluated in a field (Slatter and Hollier, 2002; Gordon and Hailin, 2010).

2.3.5 Application of nitrogenous fertilizers

Prolonged use of nitrogenous fertilizers, especially ammonium (NH_4^+) based and urea fertilizers, contributes significantly to the formation of acid soils (Bolan et al., 1991; Hart et al., 2013). Ammonium and urea fertilizers acidify the soil by releasing H^+ ions into the soil solution, as shown below. Soil microbes play an important role in these processes. However, the impact of nitrogen fertilizers on acidification varies with fertilizer type (Slattery and Hollier, 2002).

$$NH_4NO_3 + 2O_2 \longrightarrow 2NO_3^- + 2H^+ + H_2O$$

$$NH_4H_2PO_4 + 2O_2 \longrightarrow NO_3^- + H_2PO_4^- + 2H^+ + H_2O$$

$$(NH_4)_2SO_4 + 4O_2 \longrightarrow 2NO_3^- + SO_4^{2-} + 4H^+ + 2H_2O$$

$$(NH_2)_2CO + 4O_2 \longrightarrow 2NO_3^- + 2H^+ + CO_2 + H_2O$$

The acidity induced by nitrogenous fertilizers is modified by soil properties, cropping practices, and environmental factors. By boosting the export of basic cations in comparison to unfertilized soil, fertilizers may also increase the acidity of the soil (Bolan et al., 1991).

In particular, nitrates ($NO3^-$), which are highly soluble, might be transferred below the zone of the roots if they are not quickly absorbed by plants. They carry additional positively charged nutrients with them, most likely Ca and Mg, and their removal in this way causes the same acidification of the soil as removal by a crop (Bolan et al., 1991).

3. Effects of soil acidity

To carry out their typical physiological functions, plants need their own optimal soil P^H. The optimum soil P^H values for the majority of agricultural plants and soil microorganisms (bacteria, fungus, etc.) are slightly acidic, which is represented by P^H (CaCl2) = 5.2-8.0 and P^H = 5.0-7.0, respectively. In these soil P^H ranges, nearly all essential plant nutrients are readily available and soil microbes and nematodes are abundant and active. Conversely, this delicate equilibrium is upset at the extremes of high (alkaline) and low (acid) soil PH, and plant nutrients that were in sufficient supply can either become insufficient or toxic to plant development (Slattery et al., 2000). In extreme soil P^H not only plants but also the beneficial associations created between plants and soil microbes and nematodes are disturbed. Due to this, agricultural products of any kind will be less profitable and more reliant on chemical fertilizers. The availability of essential nutrients will improve when soil P^H is adjusted to a more P^H-friendly range (Slattery et al., 2000). Hence, diagnosing and understanding soil P^H aids in determining the kinds of chemical reactions that are probably occurring in soil (Neina, 2019) and provides awareness to choose the type of crops that should be grown there. Acid soil affects plant growth, development and production in a number of ways. Some of the most important effects are listed below.

3.1. Enhancing toxicity of specific elements

In acid soils, plant growth, development and productivity are limited by various toxins such as Al^{3+}, Mn^{2+}, and H^+ (Kidd and Proctor, 2000). According to Slattery et al., (1999), nutrient toxicity can happen in acid soil when the soil's P^H falls to 4.8 or below. Al^{3+} and Mn^{2+}, the two most important toxicities in acid soil (Slattery et al., 1999), are not harmful to plants at higher soil P^H. Due to their cationic nature, in strongly acidic soil ($P^HW < 4.3$) Al^{3+} and Mn^{2+} are more readily available in the soil solution and become toxic to the plant roots.

Aluminium compounds dissociate at P^H 4.5 1000 times faster than P^H 5.5, and at P^H 3.5 1000 times faster than P^H 4.5. When the pH declines from P^H 5.0 to P^H 4.0, the rate of dissociation of manganese compounds in acid soil solution is comparable to that of Al^{+3}, except that Mn^{+2} increases 100 times (McCauley et al., 2009).. This indicates that Al and Mn compounds are rapidly dissociated into their specific ions as soil P^H continuously declines, reaching toxic levels at small P^H changes.

In acidic soil, Al toxicity is recognized as the primary factor limiting agricultural outputs (Foy, 1988; Soon, 1991; Panda et al., 2009; Kochian et al., 2015). Retardation of root growth is the main symptom of aluminium toxicity (Ownby and Popham, 1989; Slattery et al., 2000; Kochian et al., 2005). Similarly, toxic concentrations of Al^{3+} in soil solution affect root cell division and root elongation capacity. Because of this, root development and branching are highly reduced (Gazey and Davies, 2009). Reduced root growth obstructs the uptake of nutrients and water, which lowers yield.

Inhibition of cell division in the root meristem zone is a typical response of cereal plants to Al exposure (Kochian et al., 2015). More than 95% of root-associated Al toxicity was reported to be localized to the cell wall, suggesting that Al is involved in the rapid displacement of Ca from the cell wall and loss of elasticity (Kinraide et al., 1994; Rengel, 2006). These changes also affect the nutrient and water uptake from the soil, thereby affecting the metabolic processes throughout plant (Quinteiro et al., 2013).

After aluminum, manganese toxicity may be the second-most significant metal toxicity in acid soils (Foy et al., 1973). Mn, in contrast to Al, is an essential plant nutrient but becomes toxic when consumed in large amounts. The Mn toxicity symptoms in plants are manifested in shoots. Mn toxicity results in stunted shoot growth and the appearance of necrotic lesions. Therefore, Mn toxicity disrupts photosynthesis by decolorizing leaves and impairs other physiological functions involved in plant growth and productivity (Gordon and Hailin, 2010).

3.2. Fixation of plant nutrients

The accessibility of essential nutrients for plants is affected by soil acidity. The solubility of a nutrient and how readily it becomes fixed (tied up) in soils determine its availability. Some readily available elements, like P, are changed by soil acidity into unavailable forms for plant uptake. Beneficial elements like Mo, P, Mg, and Ca become less accessible to plants at significantly lower soil P^H levels, whereas toxicity levels of aluminum Al, Mn, Fe, etc. remain present. For instance, between P^H 6 and 7, plants can most easily access P. According to Wild (1950), Al, Mn, and Fe oxides in acidic soils play an important role in phosphorus adsorption.

At low soil P^H (< 4), Al^{+3} and Fe^{+3} are more readily available on the cation exchange sites either in soil solution or on exposed clay surfaces. As a result, these ions react readily with phosphate ions (HPO_4^{-2} or $H_2PO_4^-$) and forms relatively insoluble compounds by the process of phosphate fixation. Because Al^{+3} and Fe^{+3} are dominant in tropical acid soils and because of this, these soils have a very high potential to fix phosphate (Elevitch and Wilkonson, 1999; Penn and Camberato, 2019). Thus, phosphate fixation is a critical problem of tropical acid soils. Not only at extremely strong soil acidity, but also P fixation with Al^{+3} is more common between P^H 4.5 and 6 and results in significant lock-up of P. Calcium phosphate is the most frequent inorganic form of P in less acidic to neutral soil P^H. In alkaline soil, Ca is the dominant ion and fixation is less permanent (Iqbal, 2012).

Figure 2 below illustrates how Fe, Al, and Ca work well together to fix P in acidic, neutral, and alkaline soils. In low P^H soils, the production of Al phosphate decreases the concentration of P in the soil solution that is controlled by precipitation reactions (Pratt, 1961). Low P availability in acidic soils is typically a significant barrier to plant growth (Nian et al., 2009).

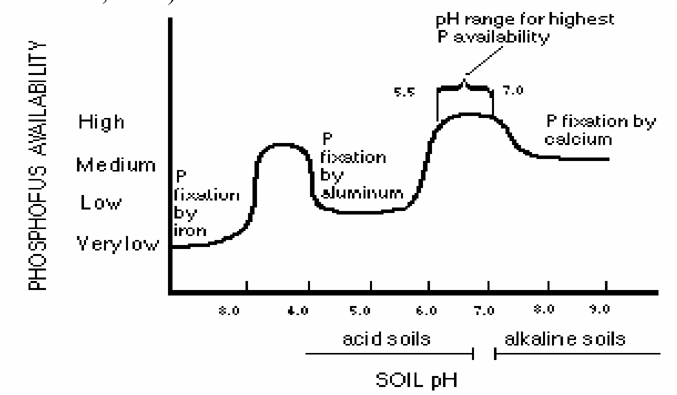

Figure 2. The fixation and availability of Phosphorous across the P^H ranges (Source: Iqbal, 2012).

3.3. Competing for exchange sites of soil colloids

Colloidal clay surfaces of the soil have negative charges that attract and hold positively charged basic cations like Mg+2, Ca+2, Na+, K+, and others. They more tightly hold the H^+ than other ions. When soil H^+ concentration rises due to acidification reactions, some of the H^+ will displace the basic cations, making the cations more likely to leach out of the soil (Hodges, 2012). If the bases are not replaced by natural or artificial means, well-drained humid area soils eventually become extremely acidic and devoid of basic cations. As the process progresses, the H+ concentration on the surface soil rises to a point where it attacks the mineral structures, releasing Si^{+4}, Fe^{+3}, and Al^{+3} as well as other ions that are present in the minerals. Si^{+4} tends to drain to lower levels, but when Fe^{+3} and Al^{+3} are liberated, they often emerge from the soil's solution as hydrous oxides (sesquioxides), which remain in the soil. With time, Kaolinite and insoluble amorphous hydrous oxides of Al+3 and Fe+3 take over as the main minerals in the soil (Robert, 2007).

3.4. Retardation of soil microorganisms' activity

In our planet, the decomposition process is mainly carried out by microbes like bacteria and fungi. Most micro-organisms obtain their metabolic inputs from the decomposition process. Extra nutrients are released into the soil where plants can absorb them if they are accessible.

Like plants, the functioning of soil microbes is affected by acidic conditions. The majority of microbial functions, such as the decomposition of organic matter and the cycling of nutrients, are slowed down in acidic soil because soil microbe growth and reproduction are inhibited.

As a result, acidic soil greatly reduces the pace at which nutrients are mineralized by soil microbes into plant-available forms, potentially reducing plant absorption. Significantly, acidic soils can prevent the establishment of symbiosis and legume nodulation (Moore et al., 1998; Gopalakrishnan et al., 2015). They cause a lack of nitrogen, which can be seen in a variety of ways, including the reddening of stems and petioles on pasture legumes or the yellowing and eventual death of the oldest leaves on legume crops.

4. Nutrient availability

Due to less availability, acidic soils are often deficient in important plant nutrients. Soil P^H affects nutrient availability primarily by altering the form of nutrients in the soil. The availability of essential nutrients can be increased by bringing the soil P^H to a recommended level.

The availability of nutrients to plants is significantly altered by soil P^H (Figures 3 & 4). Major plant nutrients including N, P, K, S, Ca, Mg, and trace elements like Mo are less readily available in acidic soils and may not be enough to support plant growth and development (Figure 3 & 4). Nutrients may not only be less chemically available to plants, but they may also be less physically accessible due to retarded root growth. Plants are unable to investigate sufficient soil volume to compensate for the decreased chemical supply when root growth is constrained. In this situation, additional fertilizers would be required for the best plant growth.

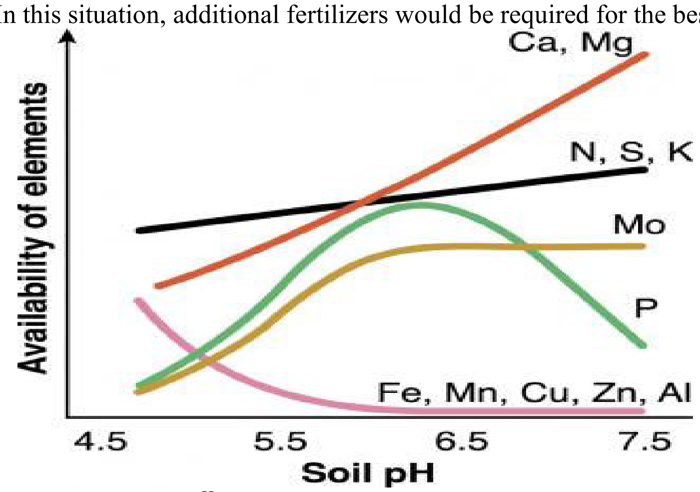

Figure 3. The relationship between P^H ($CaCl_2$) & nutrient availability (Source: Chris & Stephen, 2009)

Al^{3+}, Mn^{2+}, and Fe^{3+}, which are poisonous to plants in excess, become more soluble and available at lower P^H levels. A significant consequence of excess soluble Al3+ is that root growth is retarded and stopped. The majority of nutrients are less available at extreme P^H levels. Low PH decreases the availability of macro- and secondary nutrients, whereas high PH decreases the availability of most micronutrients.

In general, in acidic soils some mineral nutrients such as N, P, Ca, Mg, etc may not be fully available for optimal plant growth, and other mineral nutrients like Fe, Mn, Cu, Zn, etc may be present at toxic levels (Figure 4).

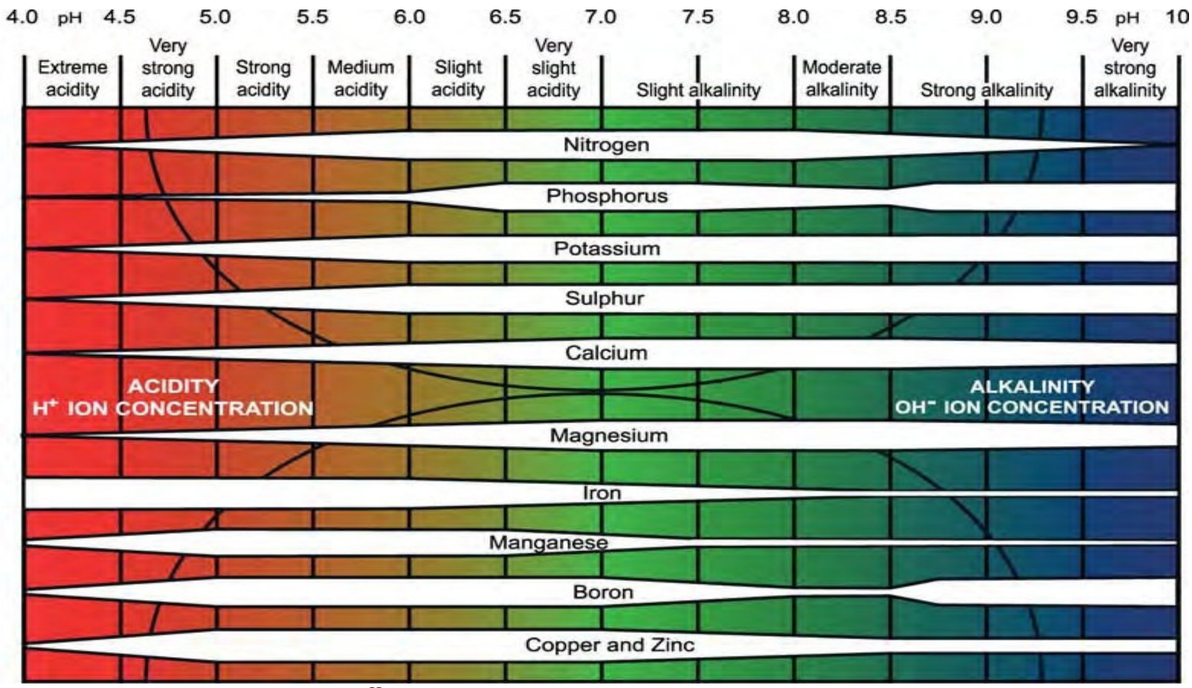

Figure 4. The effect of soil P^H on the availability of soil nutrients (Source: Truog E., 1946)

5. Phytohormonal responses to soil acidity in plants

Plant growth, development, nutrient uptake, and source/sink allocations all are significantly regulated by phytohormones (Davies, 2010; Kurepin et al., 2013a; Hüner et al., 2014; Zaman et al., 2015). These are signaling molecules that regulate a variety of physiological and biochemical processes in plants, including seed germination and dormancy (Davies, 2010; Park et al., 2015). In addition, phytohormones like abscisic acid (ABA), ethylene, cytokinins (CKs), auxins (mostly indole-3-acetic acid or IAA), and gibberellins (GAs), as well as other signaling molecules like brassinosteroids (BR), salicylic acid (SA), jasmonic acid (JA), and similar molecules, are necessary for plants to adapt to abiotic stresses because they mediate a wide range of adaptive responses (Kurepin et al., 2013b, 2015a; Ahammed et al., 2015).

Plants often decrease the levels of growth-promoting phytohormones such IAA, GAs, and CKs in response to a variety of abiotic stressors by decreasing biosynthetic activities and/or increasing catabolic activities. Since these growth-promoting phytohormones are involved in cell division and proliferation, it is not surprising that both processes involved in plant growth are typically inhibited by abiotic stressors. In contrast, plants that are abiotically stressed typically accumulate more stress-related phytohormones like ABA, SA, JA, and ethylene on occasion.

Abscisic acid is thought to have a significant role in plant acclimatization to a variety of abiotic stressors and appears to be a crucial phytohormone in plant responses to environmental changes (Zeevaart and Creelman, 1988; Cho et al., 2009; Kurepin et al., 2013b, 2015a). Upregulation in the expression of genes involved in the production of suitable osmolytes, like glycinebetaine, may result from stress-induced accumulation of ABA and SA (Jagendorf and Takabe, 2001).

The presence and activity of soil- and plant-associated microorganisms can be impacted by soil acidity (Francis, 1982; Rousk et al., 2009), which can then alter the concentrations of phytohormones in plant tissues and/or the rhizosphere. Several studies have revealed that the stress caused by soil acidity can influence the production and function of phytohormones (Yuan et al., 2009; Zhou et al., 2014).

5.1 Phytohormonal response to less available nutrients

In agroecosystem, several crops experience stunted growth and reduced yield due to acid soils. This is primarily caused by nutrient deficiencies (low levels of N, P, K, S, Ca, and Mg) and/or the toxicity of Al, Mn, and Fe (Soon, 1991; Millaleo et al., 2010). Low soil P^H inhibits root growth in many plant species (Kinraide and Parker 1987; Kinraide et al., 1994). It has been suggested that the major target of low P^H stress is apoplastic Ca2+, a crucial signaling molecule for cell growth. Higher H^+ concentration may impede root elongation due to Ca^{2+} displacement in the apoplast (Kinraide et al., 1994).

According to several experimental findings like Kova (1990) and Yuan et al., (2009), the level of CKs, IAA, and ABA detected in the seedlings of the experimental plants were significantly elevated in various proportions when exposed to low P^H for extended periods of time without influencing the level of Gas.

Amusingly, the rise in CKs, IAA, and ABA levels in response to a low P^H stress led to an increase in root hair density and root hair numbers but prevented main root elongation. This revealed that the development and extension of root tissues are tightly regulated by phytohormones (Kurepin et al., 2011a). Moreover, a reduce in main root elongation may be caused by rising ABA levels in root tissues as a result of soil acidity through localized antagonistic ABA-IAA and ABA-CK interactions (Kurepin et al., 2011a). Consequently, it can hypothesize that auxin and ethylene interact to prevent main root growth and promote the development of root hairs in plants exposed to low levels of ethylene.

According to Hiltner (1904), the rhizosphere, a zone of soil close to the roots (1-2 mm), is crucial for nutrient absorption. It controls and adjusts nutrient bioavailability based on the roots' level of acidity or alkalinity (Hue et al., 1986; Kinraide and Parker, 1987). Thus, depending on the level of cation exchange complex saturation, basic cations including K^+, Na^+, Ca^{2+}, and Mg^{2+} exhibit decreased availability at acid P^H environments around the rhizosphere (Besoain, 1985; Mora et al., 2002). Ca^{2+}, Mg^{2+}, and K^+ are significantly replaced by H^+ in acidic soils, making them more susceptible to loss by leaching and reducing the amount of nutrients available to plants (Besoain 1985; Kinraide et al., 1994). ABA plays an important role when plants are subjected to such stressful conditions.

In acidic soils, a lack of macronutrients leads to the production of ABA. Newly synthesized and/or accumulated and stored ABA is transported from roots to leaves through both xylem and phloem when the supply of essential nutrients is restricted. Once in the leaf tissues, ABA probably prevents plant from catastrophic growth halt by maintaining CO2 assimilation at a level that is below ideal but high enough to maintain physiological processes at reduced capacity (Golam and Jing-Quan, 2016).

Consequently, by promoting the catabolism of growth-active GAs, endogenous accumulation of ABA retards the growth of shoots (Kurepin et al., 2013b). Moreover, nutrient deprivation may result in comparable ABA-glycinebetaine-photosynthesis interactions, similar to the abiotic stress-mediated increase in ABA levels that supports CO2 absorption by boosting the production of glycinebetaine (Kurepin et al., 2015a).

5.2 Phytohormonal response to Al toxicity

The main factors limiting crop productivity in acidic soils are Al and Mn toxicities (Kochian, 1995; Raman et al., 2002; Tang et al., 2002). Al has significant impact on plant growth and productivity because it is the third most abundant element in the earth crust. Hence, depending on the species or genotype, the level of Al toxicity, and the level of Al tolerance, plants subjected to Al stress should alter their physiological, biochemical, and morphological properties (Delhaize and Ryan 1995; Reyes-Daz et al., 2010).

Researchers hypothesized that plants have two key defenses against the toxicity of aluminum. These are internal tolerance and external exclusion. External exclusion mechanisms are implemented by preventing entry of toxic Al^{3+} into the apoplast or symplast pathways (Kochian et al., 2004; Li et al., 2002; Pieros et al., 2005; Wang et al., 2006; Inostroza-Blancheteau et al., 2012). The mechanism that has been proposed involves the excretion of organic compounds (malate, citrate, and oxalate) from the roots that form stable complexes with the Al^{3+} in the soil solution. These complexes are less phytotoxic than free Al^{3+}, preventing the toxic Al species from entering the sensitive intracellular sites of the symplastic pathway (Ma, 2000; Li et al., 2002; Pieros et al., 2005). Conversely, the toxic Al^{3+} is immobilized, compartmentalized, or detoxified by plants using internal tolerance mechanisms in the symplasm or apoplasm. As with other stresses, the level of plant tolerance to Al toxicity varies by species, variety, or cultivar (Barceló and Poschenrieder, 2002). Native species that grow naturally on acidic soils are much more tolerant to Al stress than exotic species (Haridasan, 1982; Kochian 1995; Geoghegan and Sprent, 1996).

Inhibition of root growth, chlorosis of leaf, and stunted shoot growth are the most obvious signs of plants exposed to Al toxicity (Matsumoto, 2000; Mora et al., 2005; Rengel 2006; Reyes-Daz et al., 2009, 2010). Exacerbating the generation of reactive oxygen species (ROS) in cells, cell membranes, cellular organelles, and organic molecules, which can lead to oxidative stress and cell death, is another significant Al stress response in plants (Yakimova et al., 2007). Moreover, it has been claimed that Al alters the functioning of the chloroplast and the mitochondria, causing ROS to be produced and a signal transduction pathway that is activated by ROS to cause cell death (Kochian 1995; Kochian et al., 2004; 2015; Hede et al., 2001; Kopittke et al., 2015). To combat and withstand the phytotoxic effect of Al-induced and reduce oxidative stress, plants can activate antioxidant enzymes such superoxide dismutase, peroxidase, catalase, ascorbate peroxidase, and several secondary metabolites like flavonoids (Ma, et al., 2007).

Cellular Al toxicity causes biochemical, physiological, and morphological changes (Matsumoto, 2000; Kochian et al., 2004) to affect the metabolism and action of phytohormones (Aloni et al., 2010; He et al., 2012; Puga-Freitas and Blouin, 2015). ABA, IAA, CKs, ethylene, GAs, and JA are some of the phytohormones highly influenced by Al toxicity at acidic conditions (Kurepin et al., 2010, 2013c).

The ABA plays an important role in the response to Al toxicity. Maize (*Zea mays* L.), soybean (*Glycine max*), barley (*Hordeum vulgare* L.), pea (*Pisum sativum* L.), and buckwheat (*Fagopyrum esculentum* Moench) all showed increases in ABA production and signaling transduction (Hou et al., 2010; Reyna-Llorens et al., 2014). The increase in ABA production is directly correlated with an increase in Al toxicity present at low PH (Reyna-Llorens et al., 2014).

As a result, in Al toxic soils, the endogenous increase in ABA normally restricts plant growth, but when combined with auxin and ethylene, it stimulates the formation of root hairs on the surface of stunted main root. This is one of the major phytohormonal responses in plants against toxic mineral nutrients.

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Competing interests
The author declares that he has no competing interest

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