Role of Nutrients in Plant Growth and Development

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1 Introduction

The study of activities by which plants obtain their nutrition is called mineral nutrition. In recent decades, this area has become central to climate change, specifically environmental protection and modern agriculture. Crop yield is linearly related to fertilizer applied and its absorption. To meet the increasing food demand, the world consumption of primary elements, mainly N and P, has increased during the last few decades. However, crop plants use less than half of the fertilizer applied (Loomis and Connor 1992); remaining nutrients leach into surface water or groundwater. Some nutrients become attached to soil particles and contribute to air pollution. As a consequence of leaching, many water wells in the USA no longer meet the federal

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standards for nitrate concentrations in drinking water (Nolan and Stoner 2000). It can be stated that plants can help in recycling of animal waste and prove to be beneficial for detoxification of waste dumps (Macek et al. 2000).

Light and water must be supplied to plants for efficient utilization of nutrients. Plants are specific for their nutrient requirements and have certain optimum range for each nutrient, below which plants show nutrient deficiency symptoms. Excessive nutrient can also cause poor growth because of toxicity. Hence, adequate amount of nutrient supply is required for healthy crop production. Various tests have been developed to assess nutrient availability in soil as well as in subsequent crop plants. These data help plant scientists to determine nutrient need for a given plant in a specific soil. Availability of soil nutrients depends upon soil pH. Most micronutrients are either present in lesser concentration in soil or found as their respective salts, depending upon the pH. It has been observed that soil and plants are deficient in these essential elements; hence, there is a need to focus on this issue. Biofortification is becoming widespread, which depends on the soil–plant interactions (Olsen and Palmgren 2014; Patto et al. 2015; Tan et al. 2015). This chapter briefly describes availability of some essential nutrients, forms in which they are available to plants, their function in plants, and their availability in soil.

2 Nutrients That Limit Plant Growth and Development

Mineral nutrients have specific and essential functions in plant metabolism. Nitrogen, phosphorus, and potassium (macronutrient) are most important nutrients for plant growth and development. Nitrogen is a major component of proteins and is therefore required in higher concentration. It also catalyzes enzymatic reactions. Phosphorus is the main component of ATP and NADPH. Nucleic acids have nitrogen and phosphorus; therefore, these two mineral nutrients are the necessary requirement for any biological body (Marschner 1995).

2.1 Nitrogen

Green plants are unique in their ability to reduce atmospheric carbon via photosynthesis, and while doing this, they provide the energy source for all life. Nitrogen plays an essential role for protein and nucleic acid synthesis, which forms the living materials. Proteins are required as enzyme catalyst, while nucleic acids are required for translation of genetic material (Novoa and Loomis 1981). Nitrogen plays a role in C_3 plant photosynthesis; proteins of Calvin cycle and thylakoid represent leaf nitrogen. One study suggests that thylakoid nitrogen is proportional to chlorophyll content. Since nitrogen is a major element of leaves, in the absence of nitrogen, leaves show chlorosis. In the absence of nitrogen, leaves become yellow and this color appears in older leaves, while younger ones have mobilized nitrogen from older ones. Even in the absence of nitrogen, plants exhibit slender stem due to excess production of carbohydrates and lesser production of proteins. In this regard, the plant begins to synthesize anthocyanin and subsequent purple coloration of leaves, petioles, and stems.

2.2 Phosphorus

Phosphorus is an integral element of all membrane proteins, lipids, and nucleic acids. It plays a vital role in respiration and photosynthesis, that is, as sugar–phosphate intermediates, and is an important in energy storage or structural integrity. Its deficiency leads to stunted growth of young plants and dark green coloration of leaves. Absence of phosphorus causes small spots of dead tissues often called necrotic spots. A slight purple color may appear in leaves due to excess production of anthocyanin, but it is not associated with chlorosis. Phosphorus deficiency leads to delay in plant maturation and appearance of slender stem similar to nitrogen deficiency. To increase the yield of agricultural crops, it is required that phosphorus should be present in sufficient concentration (Tisdale and Nelson 1975; Denison and Kiers 2005). To maintain productive soils for agricultural crops, it is necessary to apply available forms of phosphorus (Sims 2000; Fixen 2005; White and Brown 2010).

2.3 Potassium

Potassium plays an important role in osmotic potential regulation of plant cells. It plays a role in enzyme activation involved in respiration and photosynthesis. Its deficiency causes mottled or marginal chlorosis and subsequently, necrosis effects mostly at the tips of leaves. Potassium is mobilized to the younger leaves; therefore, deficiency symptoms appear mainly in mature and older leaves. In case of monocots, necrotic lesions initially appear at tips and margins of leaves and then at base. Plants may also show slender and weak stems with abnormally short intermodal regions. Potassium-deficient plant roots exhibit increased susceptibility for root-rotting fungi present in the soil. It is extremely dynamic in its ionic form in plants but moderate inside soil (Ranade–Malvi 2011).

2.4 Sulfur

Two amino acids containing sulfur are constituents of vitamin complexes and coenzymes that are essential for metabolism. Symptoms of sulfur deficiency are mostly similar to nitrogen deficiency, including chlorosis, stunting of growth, and anthocyanin accumulation, since sulfur and nitrogen both form the basic structure of proteins. Nitrogen deficiency causes chlorosis in older leaves, while sulfur deficiency occurs initially in mature and older leaves due to the fact that in most species, sulfur is not easily remobilized to the younger leaves.

2.5 Calcium

In cell wall synthesis, calcium plays a crucial role, especially in case of middle lamellae. It plays a significant role in mitotic spindle formation required for proper functioning of membranes and also serves as the second messenger for signaling processes. It forms the calcium–calmodulin complex, a protein found in cytosol, which regulates many metabolic process. Its deficiency leads to necrosis at tips of roots and young leaves. Since it is involved in cell wall synthesis, its deficiency leads to death of young meristematic regions.

2.6 Magnesium

Magnesium ions have a specific role in activation of some enzymes that are involved in synthesis of nucleic acid, respiration, and photosynthesis. It is a part of the chlorophyll molecule. Its deficiency causes chlorosis; in case of extensive deficiency, leaves may become white or yellowish. Premature leaf abscission may also occur due to its deficiency.

3 Micronutrients

Micronutrients are those elements that are required in lesser quantities and necessary for plant metabolic activities, specifically enzyme activation for reaction catalysis (Epstein 1965).

3.1 Boron

Till now, the precise function of Boron is not clear; it is suggested that it plays a vital role in cell elongation nucleic acid synthesis. This micronutrient is essential for the normal growth of plants and certain diatom species. Its deficiency causes anatomical changes with corresponding change in physiology and biochemistry of cell. But it is difficult to determine the primary role of boron; probably it is involved at membrane-level functions. Other possible roles of boron are sugar transport, integrity of cell wall structure, lignification, respiration, IAA metabolism, and phenol metabolism. The available concentration of Boron may vary from soil to soil, while it is reported in range of 20–200 mg B/Kg (Ahmad et al. 2012).

3.2 Zinc

Zinc in its ionic form is required by plants for enzyme activation involved in many metabolic activities such as DNA replication, for activation of DNA polymerases, and for chlorophyll biosynthesis in some plants, hydrogenase and carbonic anhydrase stabilization of ribosomal fractions, and synthesis of cytochrome (Tisdale et al. 1984). Deficiency of zinc appears as reduction in intermodal growth resulting in growth. The leaves may appear small. Chlorosis of plant leaves infers requirement of zinc for chlorophyll biosynthesis. Plants activated by zinc are also involved in carbohydrate metabolism and pollen formation (Marschner 1995). Zinc is required for tryptophan biosynthesis, which is a precursor of auxin, hence required for hormone biosynthesis (Alloway 2004). Interaction of zinc with sulfhydryl group of membrane proteins and phospholipids helps in membrane maintenance (Kabata-Pendias and Pendias 2001; Dang et al. 2010; Alloway 2004).

Zinc deficiency is widespread and crops respond positively to application of zinc (Welch 2002). Zinc is present in soil primarily due to geochemical and pedochemical weathering process from rocks. The amount of zinc in soil depends on the type, intensity of weathering, and other climatic factors that affect soil genesis (Saeed and Fox 1977).

Availability of zinc in soil reduces due to high pH, high $CaCO_{3,}$ clay, and phosphate, as these factors fix available zinc in soil (Imtiaz 1999). Zinc is generally found at a lower concentration in acidic and sandy soil. About 30% of cultivable land soil of the world contains low levels of Zinc (Sillanpaa 1990).

The change in pH affects the availability of zinc in soil because of formation of insoluble complexes. It usually forms complexes with Mn and Fe hydroxides (Sajwan and Lindsay 1988) Microorganisms play a key role in availability of nutrients; among the nutrients, Zinc is the cofactor and mineral activator of many enzymes (Venkatakrishnan et al. 2003). At a higher level, it might limit the cell and bacterial growth (Baath 1992).

3.3 Manganese

Manganese in its ionic form is required by plants for the activation of enzymes, specifically those that are involved in TCA and ETS. It helps in the assimilation of carbon dioxide during photosynthesis and evolution of oxygen from water-splitting complex (Marschner 1995) and chlorophyll biosynthesis. Its activity is required in the formation of ascorbic acid, riboflavin, and carotene. It is a necessary element required by plant in lesser concentration; hence, it may become toxic for plant when available in excess and interfere with utilization of other minerals such as Ca, Mg, Fe, and P via some inhibitory effects on absorption and translocation (Clark 1982). High concentration of Mn affects enzymatic activities and hormonal balance in plants; hence, Mn catalyzed reaction becomes less active or sometime nonfunctional (Horst 1988). Intervenous chlorosis (chlorophyll deficiency) with consequent development of necrotic spot is a major symptom of Mn deficiency. Depending upon plant species, it may occur in younger or older leaves. Deficiency of micronutrients in soil is widespread; many millions of hectares of arable land in the world are deficient in one or more micronutrients (Rengel 2015).

Availability of Mn in soil depends on the oxidation state of this element; it has been observed that Mn^{4+} is unavailable for plants, while it is available as Mn^{2+} (reduced form). Reduction may be biological or chemical in nature (Rengel 2000). At alkaline pH, the availability of Mn may decrease; however, the chemistry of that Mn is not clear (Clark and Baligar 2000; Pan et al. 2014). It has been observed that the concentration of Mn^{2+} in soil decreases 100 fold with every unit increase in pH (Barber 1995). Supply of Mn is a complex variable that is dependent not only on soil chemistry but also on responses of plants and microorganisms. The mechanism for mobilization of Mn surrounding the root zone via root exudate is not clear (Gherardi and Rengel 2004; Mora et al. 2009; George et al. 2014). Nutrient deficiency symptoms in plants occur when the amount of nutrient required is below that permissible or optimum range in the soil that cannot be taken up by plants. This may occur due to low solubility of nutrients, or poor soil–microbe–plant interactions (Marschner et al. 2011).

3.4 Molybdenum

Molybdenum is a transition metal required by plants for the activation of enzymatic reactions including nitrogen assimilation, purine degradation, hormone synthesis, and sulfite detoxification. It is actually inactive in its native state and needs to be complexed by specific organic pterin, which serves as a prosthetic group, molybdenum cofactor. Recent studies reveal that the concentration of molybdate is controlled by molybdate transporters (Bittner 2014). Molybdenum and iron have a close connection, as most molybdo enzymes need iron containing redox groups. These ions are components of enzymes as nitrate reductase and nitrogenase. Deficiency of this element indicates chlorosis between veins and necrosis of older leaves. It may prevent flower formation and also nitrogen deficiency, if the plant depends on symbiotic nitrogen fixation. Plants require molybdenum in very low concentration; hence, in molybdenum-deficient soil, supply of molybdenum in small quantity may increase crop production.

In soil, availability of molybdate is favored above pH 5.5 and lesser pH impairs the availability absorption by soil oxides. Under lower pH conditions, its assimilation is limited leading to molybdenum deficiency and subsequent reduction in yield and growth of plants. It can be overcome by fertilization. Excess molybdenum characterized by yellowish leaves *(*Kaiser et al. 2005) and reduction in anthocyanin and seedling growth (Kumchai et al. 2013).

Molybdenum concentration in agricultural soil ranges from 0.2 to 5.0 mg/kg (Scheffer and Schachtschabel 2002). Soil solutions have molybdate ions, which are available to plants. The content of Fe, Mn, Al oxides, clay minerals, and organic carbon influences availability of Mo. Soil pH has a major role on the release of ions into the soil solution. It is observed that at pH range from 4 to 5, maximum adsorption of molybdenum occurs on positively charged metal oxides (Riley et al. 1987; Xie et al. 1993; Gupta 1978; Xu et al. 2013).

In acidic conditions, anions of molybdate are adsorbed on Fe, Mn, and Al oxides, on clay minerals and organic colloids. Its availability increases with pH through decreased adsorption of metal oxides (Jiang et al. 2015; Smith et al. 1997). Well-drained sandy soils have a lesser concentration of molybdenum due to leaching, while wet soil tends to accumulate higher levels (Riley et al. 1987).

In one study, the concentration of molybdenum in the soil solutions was determined and it was observed that it ranges from 0.002 to 0.100 μmol/L. It was also differentiated depending on different properties of soil. In one study, some soil parameters have been analyzed; among them, soil pH has been suggested to be the most important factor that affects the concentration of Mo in soil solution. It has been observed that in acid sandy soils, the Mo concentration in the soil solution is too low to sustain the nutritional need of the plants. Regular liming of soils and phosphorus supply can improve the availability of molybdenum to plants (Rutkowska et al. 2017).

3.5 Iron

Iron plays an important role as enzyme component, which is involved in electrons transfer reactions (redox reactions). It is reversibly oxidized from Fe^{2+} to Fe^{3+} during electron transfer. Intervenous chlorosis is a characteristic symptom of iron deficiency. In cases of prolonged deficiency, the veins may also appear chlorotic, turning the whole leaf to white. As iron is required for chlorophyll–protein complex synthesis, leaves may become chlorotic. Due to its precipitation in the older leaves, low mobility of iron as insoluble oxides or phosphates is observed. Complexes with phytoferritin, an iron-binding protein, are also observed in the leaf and other plant parts (Oh et al. 1996).

3.6 Copper

Similar to iron, copper is an element associated with enzymes that are involved in redox reactions. Plastocyanin, an enzyme involved in electron transfer during light reactions of photosynthesis is one example (Haehnel 1984). Dark green leaves, which may contain necrotic spots, are an initial symptom of copper deficiency. Leaves may abscise prematurely under extreme copper deficiency.

3.7 Nickel

Nickel, the 22nd most abundant element in the earth's crust, is found in natural soils in trace concentrations (Hussain et al. 2013). It is an essential element for metabolic activities of plants and many bacteria (Brown 2007). Ni is present in several enzymes in prokaryotes (e.g., glyoxalase-I, hydrogenases, some superoxide dismutases, carbon monoxide dehydrogenase, and methyl-coenzyme M reductase (Ragsdale 1998)), while urease is the only known nickel-containing enzyme in higher plants (Polacco et al. 2013). Nickel plays an important role in nitrogen fixation; nitrogen-fixing microbes require nickel for the enzymes that reprocess hydrogen gas liberated during fixation. Nickel deficiency appears in plants as leaf tip necrosis and urea accumulation. However, these symptoms occur rarely in plants.

3.8 Chlorine

Chlorine in its ionic form is required by plants during photosynthesis in water-splitting complex. It plays a role in cell division in leaves and roots (Harling et al. 1997; Clarke and Eaton-Rye 2000). Bronze like color appears in plant leaves due to chlorine deficiency; it may show stunted and thickened root tips. Some plants absorbed higher concentration of chlorine than required by plants for normal metabolic activities.

4 Availability of Mineral Nutrients in Soil

One of the most important components of organic material is nitrogen, next to carbon. Both these are essential for fertility of soil. The biogeochemical cycle of C and N plays an important role in global warming (Yang et al. 2010). The ratio of these two regulates the mineralization process in soil, specifically organic matter, which eventually releases soil nitrogen (Deng et al. 2013). Mineralization occurs via decomposition process. Significant decline in carbon storage has been observed due to change in C and N ratio (Aitkenhead and McDowell 2000). There are many factors that influence the biogeochemical cycle, namely climate, topography, and some basic soil properties, which eventually change the C and N storage. Land use is the most significant factor among all (Yang et al. 2010). Organic matter is the main source of carbon in soil and C:N represents its degradation. Since soil mechanism is governed by climate factors, soil organic carbon is the main factor that determines some important component of terrestrial ecosystem (Sakin et al. 2010; Garcia and Alcantara 2013; Zhang et al. 2007). Regarding N and P, their cycling shows many differences. The main source of N is atmosphere, while P is derived from rock weathering; due to this fact, the former one is usually absent in newly formed soil, thus not involved in net primary productivity (Tilman 1986; Berendse 1990; Vitousek et al. 1987).

Due to the mobile nature of nitrogen in soil, it is leached away; it can easily move from the ecosystem in a gaseous form as in cases of frequent fires and denitrification. Therefore, on the extent of nitrogen losses, soil may remain N limited for a long period of time. Nitrogen is carbon-bonded, while phosphorus is ester-bonded and often soluble, hence easily available for plants to absorb (Hunt et al. 1983; Howarth 1988), while carbon-bonded nitrogen is immobilized for a long time and thus promotes nitrogen limitation. Biochemistry is not the only feature that is responsible for this difference, but the external environment also affects the nitrogen and phosphorus availability. Since these are essential nutrients required by plants in excess, there is a need to determine the limitation of these elements in plants and soil (Boeye et al. 1997). Factorial fertilizer experiment can be used for macronutrients estimation, but these are time consuming, laborious, and impart some disturbances. Interpretation of such results causes difficulty due to disturbances at specific sites (Bobbink 1992). Plant responses for nutrient addition are affected by chemical adsorption and microbial immobilization.

One group of researcher has suggested that N:P mass ratios in plants indicate the limitation of certain nutrients (Koerselman and Meuleman 1996), but it is difficult to assess at community and species level; further, the N:P ratio is itself a limiting factor for plant growth and development (DiTomasso and Aarssen 1989). Plants grown in soil with lower fertility have high capacity to uptake mobile ions (Veerkamp and Kuiper 1982) and a comparatively lower capacity to absorb immobile ions (Chapin et al. 1986; Raab et al. 1998). Nitrogen found in the soil in the form of nitrate, ammonium, and as organic nitrogen, so plants absorb any form of nitrogen (soluble form), depending upon their preferences on the basis of different carrier proteins (Atkin 1996). It is reported that in Arctic plants, where a high concentration of amino acid occurs, plant growth preferentially depends on amino acids (Keilland 1994), while spruce grows on acidic soil, absorbs ammonium instead of nitrate (Kronzucker et al. 1997).

pH is a relevant property of soil which can even determine the yield of certain crops (Moody et al. 1998). It is a dynamic feature with significant differences (Behera and Shukla 2015; Kariuki et al. 2010). These differences are due to seasonal variations. During rainfall when evapotranspiration exceeds precipitation, salt concentration increases, which forces H^+ ions in soil, thereby decrease in pH, whereas in wet seasons, soil salts are removed, and hence, pH increases (Rengel 2002). These fluctuations are seasonal and not to be confused with changes in pH over centuries (Tang and Rengel 2003). Soil pH is an important factor, which has a dominant effect on the solubility and availability of ions (Clark and Baligar 2000). Iron toxicity occurs in soil with pH (<3.2), that is, acidic and anaerobic conditions

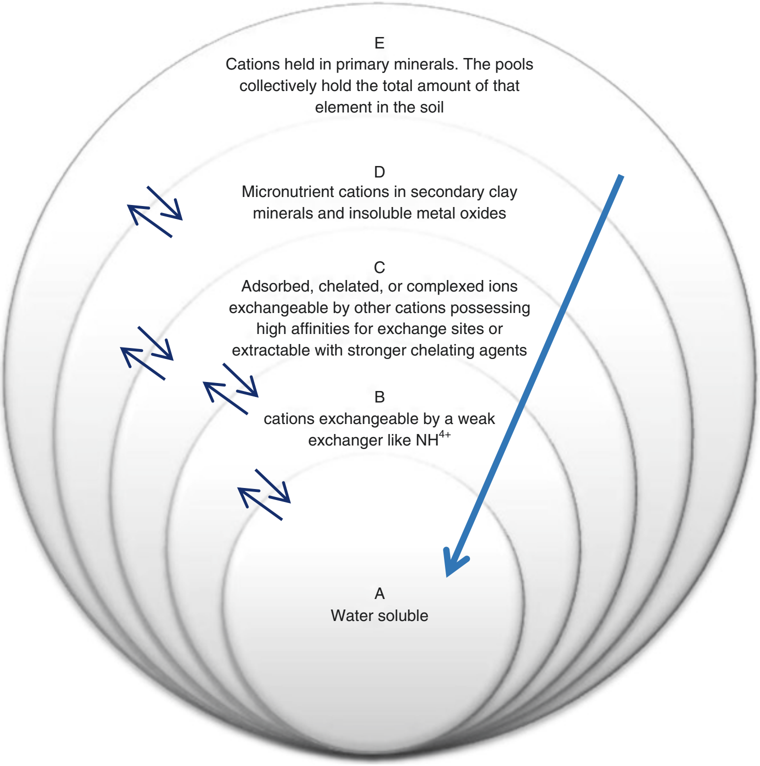

Fig. 1 Five major cation pools of micronutrients

(Khabaz-Saberi et al. 2010). Sometimes, manganese becomes toxic in poorly drained soil when reducing conditions dominate.

Micronutrient cations occur mainly in five pool types on the basis of their availability and solubility. These are postulated as A, B, C, D, and E (Fig. 1).

Pool A consists of non-adsorbed ions and ions adsorbed on colloids. Soil pH, redox potential, and concentration of other ions affect this zone in terms of ions present in this pool. In this pool, small or lesser concentration of Zn and Cu is observed, while Mn and Fe may be present in very smaller concentration (< 1 ppm). Low redox potential and low pH can increase the pool size for Mn and Fe, but has negligible effect on Zn and Cu.

Pool B includes water-soluble pool A and is larger than A. However, it is smaller for Zn and Cu except for some in which fertilization has been done for these elements. To predict the adequacy of Mn, exchangeable Mn of pool B is frequently used (Sherman 1957).

Pool C contains those cations which can be exchanged by the mass action of cations with affinities for the absorbent or by extraction through chelating agents. It has been suggested that this pool contains cations absorbed with great affinity by clay and humus of the soil.

It has been found that pool A, B, and C are in reversible equilibrium shown in Fig. 1 (designated by double arrows). The availability of micronutrients in these pools is greater than that of others, especially in pool C.

Pool D and pool E consist of secondary minerals around these three pools. These two cannot be separated by chemical methods due to precipitation of secondary minerals being highly resistant to weathering (Viets 1962).

Temperature, after pH, is the major factor, which can regulate biogeochemical processes, for example, soil respiration (Raich and Schlesinger 1992), N mineralization and nitrification (MacDonald et al. 1995), litter decomposition (Meentemeyer 1978; Jansson and Berg 1985; Hobbie 1996), denitrification (Malhi et al. 1990), CH_4 emission (Crill et al. 1988; Crill 1991; Johnson et al. 1996), fine root dynamics (Boone et al. 1998; Pregitzer et al. 2000; Gill and Jackson 2000), plant productivity (WarrenWilson 1957), and plant nutrient uptake (BassiriRad 2000). Anthropogenic activities have an impact on increased concentration of green house gases (Intergovernmental Panel on Climate Change (IPCC) 1996). Green house gases have a potential ability to capture heat energy and thus increased global mean temperature by 0.3–0.6 °C over the last century (IPCC 1996; Rind 1999; Karl et al. 2000). Global warming affects most of the processes on earth; however, it is not clear which processes will be most affected by warming. One researcher has reported that there are some factors that affect ecosystem response, such as stocks and initial turnover rates of labile soil C and N, relative size of the plant and soil C pools, dominant form of available N in the soil, soil water and precipitation regimes, the chemical composition and turnover rates of plant residues, and the longevity of individuals and population turnover rates of dominant species (Shaver et al. 2000) and availability of minerals in soil. Soil respiration rates generally increase with warmer temperatures (Peterjohn et al. 1993, 1994; McHale et al. 1998; Rustad and Fernandez 1998). Plant productivity have all been shown to be affected by climate warming (Van Cleve et al. 1990; Joslin and Wolfe 1993; Peterjohn et al. 1993, 1994; Harte and Shaw 1995; Hantschel et al. 1995; Robinson et al. 1995; Hobbie 1996; Lukewille and Wright 1997; Ineson et al. 1998; Jamieson et al. 1998).

5 Conclusion

Mineral nutrients are essential for plant growth and development. They are present in soil in the form of either cation or anion, depending upon their oxidation and reduction reactions. Availability of these elements is much affected by pH of the soil. It has been observed that alkaline pH is not favorable for soil health because these soils are either micronutrients-deficient or have lesser concentration of the same. Besides pH, temperature is another aspect that affects nutrient availability and other more parameters of soil and surrounding environment. Researches have proved that increase in temperature has a significant effect on ecosystem responses, including biogeochemical cycling. Due to disturbances in this cycle, the whole criteria that play governing role for ecosystem functioning have changed. Since nutrients are the major source for growth and development of plants, and the reservoir of these nutrients is soil, it is a necessary field of study with a broad scope. As India is the country of farmers and most of the population depends on agriculture, a great attention is a need of today. In this regard, necessary steps should be taken by keeping in mind the basic criteria of fertilizer supply and this can be done only when one has a knowledge of appropriate concentration of nutrients and factors that govern availability of the same.

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