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Soil Mineral Macronutrients for Maximizing Growth and Productivity in Higher Plants

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Abstract: Plants require a sustained and balanced supply of nutrients during the growing season for maximum growth and yield. Nitrogen, phosphorus, potassium, sulfur, calcium and magnesium are the mineral nutrients required by most plants in the highest concentration and thus they are defined as macronutrients. Because the requirement for these nutrients is quantitatively large, deficiency can be more common than for elements that are needed in only minute quantities. Nitrogen, phosphorus and potassium are primary macronutrients but sulfur, calcium and magnesium are secondary macronutrients because requirements are substantially less than the primary macronutrients but their requirements are still hugely more than the micronutrients. A less than adequate supply of any one of these essential elements will lead to metabolic disruptions, including changes in activities of enzymes, rate of metabolic reactions and concentration of metabolites. In addition to alterations in metabolic patterns, severe deficiencies of individual essential elements also produce a set of characteristic effects in the external appearance of leaves, stems, roots and seeds. Several physical, chemical and biological properties of soil interact to determine the concentration of available nutrients in the soil. Soil pH is arguably the most important because it influences the chemical form of nutrients and their availability. The optimum pH for most nutrients is generally from 6.5–7.5. Outside this range, the concentration of many nutrients in the soil solution declines. Moreover, nutrients interaction in the soil affects plant growth and yields. Hence, understanding each nutrient interaction with other nutrients is important to improve crop yields and to promote efficient nutrients management. Deficiencies, toxicities and imbalances can be diagnosed in plants visually or through soil and plant analysis. A nutrient imbalance occurs when the availability of one nutrient induces a deficiency or toxicity in another. It can result from a natural imbalance of available nutrients in the soil caused by sodicity, salinity, or extremes in soil pH. A nutrient imbalance can also be caused by fertilizer practices that apply a nutrient at a high enough rate to interfere with the uptake of other nutrients. However, the adoption of appropriate management practices may overcome nutrient deficiency and enhance nutrient use efficiency in crop plants. Therefore, the management of nutrients is an important aspect of plant growth and improving crop productivity.

Key words: Deficiency Symptoms · Macronutrients · Nutrient Toxicity · Nutrient Uptake · Minerals

INTRODUCTION

Mineral nutrition refers to the supply, availability, absorption, translocation and utilization of inorganically formed elements for the growth and development of crop plants. Essential nutrients may be defined as those without which plants cannot complete their life cycle, are irreplaceable by other elements and are directly involved in plant metabolism [1, 2]. Each essential element performs a specific biochemical or biophysical function within plant cells. Hence deficiency of even one of these elements can impair metabolism and interrupt normal development [3]. Nutrient requirements of crops depend on yield level, crop species, cultivar or genotypes within species, soil type, climatic conditions and soil biology. Hence soil, plant and climatic factors and their interactions are involved in determining plant nutrient requirements. In addition to this, the economic value of a crop and the socioeconomic

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conditions of the farmer also are important factors in determining the nutrient requirements of a crop. From the viewpoint of sustainable agriculture, nutrient management ideally should provide a balance between nutrient inputs and outputs over the long term [4, 5]. In the establishment of a sustainable system, soil nutrient levels that are deficient are built up to levels that will support economic crop yields. To sustain soil fertility levels, nutrients that are removed by crop harvest or other losses from the system must be replaced annually or at least within the longer crop rotation cycle [5]. When nutrient buildup in soils exceeds plant removal, nutrient leaching and their removal in runoff become an environmental concern [5, 6]. Accurate values for crop nutrient removal are an important component of nutrient management planning and crop production [5].

Agricultural production and productivity are directly linked with nutrient availability and uptake. Plants take up nutrients from the soil throughout the growing season but the pattern of nutrient uptake differs from that of dry matter production. Initial uptake of nutrients is more rapid than dry matter production but uptake of nutrients slows as the crop approaches maturity. The nutritional requirements of the developing grain are largely met by mobilization from leaf and stem tissues and, to a lesser extent, by absorption of nutrients from the soil. Nutritional disorders are common in almost all field crops worldwide. The magnitude varies from crop to crop and region to region. Even some cultivars are more susceptible to nutritional deficiencies than others within a crop species [7]. Diagnostic techniques for nutritional disorders are the methods for identifying nutrient deficiencies, toxicities, or imbalances in the soil-plant system [8]. Soil properties are not the only determinant of the nutrient status of crops. There is considerable variation in the ability of plants to cope with different nutrient deficiencies and toxicities. The occurrence of a nutritional problem may reflect the sensitivity of a plant species or variety to a nutrient deficiency or toxicity as well as the specific properties of the soil. Nutrient deficiencies in crop plants may occur due to soil erosion; leaching to lower profile; intensive cropping system; denitrification; soil acidity; immobilization; heavy liming of acid soils; infestation of diseases, insects and weeds; water deficiency; and low application rates. Similarly, nutrient or elemental toxicity may occur due to excess, imbalance and unfavorable environmental conditions. Therefore, this review paper was summarized to investigate the importance of macronutrients for improving the growth and productivity of higher plants.

Plant Nutrients: Understanding the principles of soil fertility is vital to efficient nutrient management, crop production, as well as environmental protection [9]. There are 17 chemical elements known to be essential for plant growth and 14 of these elements come from the soil. Each essential plant nutrient is needed in different amounts by the plant, varies in mobility within the plant and varies in concentration in harvested crop components. It is useful to know the relative amount of each nutrient that is needed by a crop and the relationship between amounts removed with crop harvest. To be classified as essential, the element needs to meet the following criteria: (1) the plant cannot complete its life cycle (seed to new seed) without it; (2) the element's function cannot be replaced by another element; and (3) the element is directly involved in the plant's growth and reproduction. Three elements, carbon (C), hydrogen (H) and oxygen (O), are non-mineral nutrients because they are derived from air and water, rather than from soil. Although they represent approximately 96% of plant biomass, they are generally given little attention in plant nutrition because they are always insufficient supply. The macronutrients represent 0.1 - 5% or 100-5000 ppm of dry plant tissue, whereas the micronutrients comprise less than 0.025% or 250 ppm. However, other factors such as soil management and the environment can influence the availability and crop growth response [10]. The 14 essential plant mineral nutrients are classified as either macronutrients or micronutrients based on their plant requirements and relative fertilization need (Table 1).

Plant Uptake of Nutrients: Each nutrient cannot be taken up by plants in its elemental form, but instead is taken up in an 'ionic' or charged form, except B as uncharged boric acid (Table 2). Most fertilizers are made up of combinations of these available nutrient forms, so when the fertilizer dissolves, the nutrients can be immediately available for uptake. Knowing what form of a nutrient the plant absorbs helps us to better focus on what controls the cycling and movement of that nutrient in the soil. Besides, understanding nutrient functions and mobility within the plant are useful in diagnosing nutrient deficiencies. Nutrient uptake by roots is dependent on the activity of the root, ability to absorb nutrients and nutrient concentration at the surface of the root [11]. Roots come directly in contact with some nutrients as they grow; however, this only accounts for a very low percentage of the total amount of nutrients taken up by plants. Therefore, other mechanisms must cause the movement of nutrients to the plant. Water moves toward

Table 1: Essential plant elements, source, roles and relative quantities in plant

Element	Source	Role in plant	Concentration
Carbon (C)	Air	A constituent of carbohydrates; necessary for photosynthesis	45%
Oxygen (O)	Air/Water	A constituent of carbohydrates; necessary for respiration	45%
Hydrogen (H)	Water	Maintains osmotic balance; important in many biochemical reactions; a constituent of carbohydrates	6%
Nitrogen (N)	Air/Soil	A constituent of amino acids, proteins, chlorophyll and nucleic acids;	1-5%
Potassium (K)	Soil	involved with photosynthesis, carbohydrates translocation, protein synthesis	0.5-1%
Phosphorous (P)	Soil	A constituent of proteins, coenzymes, nucleic acids and metabolic substrates; important in energy Transfer	0.1- 0.5%
Magnesium (Mg)	Soil	Enzyme activator; component of chlorophyll	0.1- 0.4%
Sulfur (S)	Soil	Component of certain amino acids and plant proteins	0.1- 0.4%
Chlorine (Cl)	Soil	Involved with oxygen production and photosynthesis	0.01- 0.1%
Iron (Fe)	Soil	Involved with chlorophyll synthesis and in enzyme electron transfer	50-250ppm
Manganese (Mn)	Soil	Controls several oxidation-reduction systems and photosynthesis	20-200ppm
Boron (B)	Soil	Important in sugar translocation and carbohydrates metabolism	6-60ppm
Zinc (Zn)	Soil	Involved with enzymes that regulate various metabolic activities	25-150ppm
Copper (Cu)	Soil	The catalyst for respiration; component of various enzymes	5-20ppm
Molybdenum (Mo)	Soil	Involved with nitrogen fixation and transforming nitrate to ammonium	0.05-0.2ppm
Nickel (Ni)	Soil	Necessary for the proper functioning of urease and seed germination	0.1-1ppm

Table 2: Essential plant nutrient forms are taken up by plants

Element	Form
Nitrogen (N)	NO_3^- (nitrate), NH_4^+ (ammonium)
Potassium (K)	K^+
Phosphorous (P)	$H_2PO_4^-$, HPO_4^{-2} (phosphate)
Calcium (Ca)	Ca^{+2}
Magnesium (Mg)	Mg^{+2}
Sulfur (S)	SO_4^{-2} (sulfate)
Chlorine (Cl)	Cl^- (chloride)
Iron (Fe)	Fe^{+2} (ferrous), Fe^{+3} (ferric)
Manganese (Mn)	Mn^{+2}
Boron (B)	H_3BO_3 (boric acid), $H_2BO_3^-$ (borate)
Zinc (Zn)	Zn^{+2}
Copper (Cu)	Cu^{+2}
Molybdenum (Mo)	MoO_4^{-2} (molybdate)
Nickel (Ni)	Ni^{+2}

and into the root as the plant use water or transpires. This process, called 'mass flow', accounts for a substantial amount of nutrient movement toward the plant root, especially for the mobile nutrients such as NO_3^-. Specifically, the mass flow has been found to account for about 80% of N movement into the root system of a plant, yet only 5% of the more immobile P. It has been found that 'diffusion' accounts for the remainder of the nutrient movement. By fertilizing near the plant root, the plant is less dependent on exchange processes and diffusion to uptake nutrients, especially P. The nutrients that are most dependent on diffusion to move them toward a plant root are relatively immobile, have relatively low solution concentrations and yet are needed in large amounts by the plant, such as P and K [12]. The secondary macronutrients (Ca, Mg and S) often do not depend on diffusion because their solution concentrations are fairly high in soil relative to plant requirements.

Nutrient Mobility Within the Plant and Soil: All nutrients move relatively easily from the root to the growing portion of the plant. Interestingly, some nutrients can also move from older tissue to newer tissue if that nutrient is deficient. The terminology used to describe the nutrient deficiency in plants is indicated in Table 3. Knowing which nutrients are 'mobile' (i.e., more able to move) is very useful in diagnosing plant nutrient deficiencies because if only the lower leaves are affected, then a mobile nutrient is most likely the cause. Conversely, if only the upper leaves show the deficiency, then the plant is likely deficient in an 'immobile' (i.e., less able to move) nutrient because that nutrient cannot move from older to newer tissue (leaves). S is one element that lies between mobile and immobile elements depending on the degree of deficiency. Nutrient deficiencies, toxicities and imbalances can be diagnosed from plant appearance, soil test and plant test [13]. Plant tissue tests are generally the best

Table 3: The terminology used to describe deficiency symptoms in plants

Term	Definition
Chlorosis	A yellowing or lighter shade of green
Necrosis	Browning or dying of plant tissue
Interveinal	Between the leaf veins
Meristem	The growing point of the plant
Internode	The distance of the stem between the leaves
Mobile	A mobile element is one that can translocate, or move, from one part of the plant to another depending on its need. Mobile elements generally move from older (lower) plant parts to the plant's site of most active growth (meristem).

Table 4: Mobile and immobile essential nutrients in plants

Mobile nutrients	Immobile nutrients
Nitrogen (N)	Sulfur (S)
Phosphorous (P)	Calcium (Ca)
Potassium (K)	Iron (Fe)
Chloride (Cl)	Zinc (Zn)
Magnesium (Mg)	Manganese (Mn)
Molybdenum (Mo)	Boron (B)
	Copper (Cu)
	Nickel (Ni)

way of quantifying the nutritional status of the crop. Soil tests indicate the amount of the nutrient in the soil and the potential availability of nutrients to plants. The critical level of nutrients in soils and plants for deficiency or toxicity varies with crop and crop age, variety and soil type [14]. Negatively charged ions (anions) usually leach more readily than positively charged ions (cations) because they are not attracted to the predominantly negative charge of soil colloids. For example, NO_3^-, due to its negative charge and relatively large ionic radius, is not readily retained in the soil and is easily lost from soils by leaching. An exception to this behavior is phosphorus anions (HPO_4^{2-}, $H_2PO_4^-$). These anionic forms do not easily leach through the soil profile because of their specific complex reactions with soil components. Table 4 lists the six mobile and eight immobile mineral nutrients in plants.

Nutrient Cycle in Soil-Plant Systems: The cycle of a nutrient in the soil-plant system can be defined as addition, transformation and uptake by plants, loss from the soil-plant system and immobilization. The nitrogen (N) cycle in the soil-plant system is very dynamic and complex due to the involvement of climatic, soil and plant factors. Knowledge of the nutrient cycle in the soil-plant system is an important aspect of understanding the availability of N to plants and adopting management practices to maximize its uptake and use efficiency [15]. The main input sources of N to the soil-plant system are chemical fertilizers, organic manures and biological N_2 fixation. Similarly, the main N depletion sources in the soil-plant system are leaching, denitrification, volatilization, surface runoff and plant uptake. The N immobilization also has a temporary influence on N uptake to plants. The N immobilization is defined as the transformation of inorganic N compounds (e.g., NH_4^+, NO_3^-, NO_2^- and NH_3) into the organic state. More than 90% of the N in most soils is in the form of organic matter. The organic form of N protects the N from loss; however, it is also not available to crop plants. This organic form of N should be mineralized to NH_4^+ and NO_3^- before its uptake by plants. Mineralization is the conversion of an element from an organic form to an inorganic state as a result of microbial activity [16]. The initial conversion to NH_4^+ is referred to as ammonification and the oxidation of this compound to NO_3^- is termed nitrification. The nitrification process, which occurs in two phases in the soil-plant system, can be represented by the following equations:

$$2NH_4^+ + 3O_2 \circledcirc 2NO_2^- + 2H_2O + 4H^+$$
$$2NO_2^- + O_2 \circledcirc 2NO_3^-$$

Nitrification results in the release of H^+ ions, leading to soil acidification. Nitrate ions are negatively charged and easily leach under heavy rainfall or irrigation. The amount of N leached depends on soil type, source of N fertilizer, crops and methods of fertilizer application. Also, nitrate is a major factor associated with the leaching of such bases as calcium, magnesium and potassium from the soil. The nitrate and bases move out together. As these bases are removed and replaced by hydrogen, the soil becomes more acid. Nitrogen fertilizers containing such strong acid-forming anions as sulfate increase acidity more than other carriers without acidifying anions [17]. Denitrification is a major loss of N from the soil-plant system and it is mainly anaerobic bacterial respiration. Denitrification is influenced by several factors like soil pH, temperature, organic C supply, nitrate concentration, aeration and water status [18]. Ammonia volatilization is an important process of N loss from soil-plant systems when nitrogen fertilizers are surface applied, especially in alkaline soils. The loss of NH_3 through the plant canopy can occur during the whole growth cycle of a crop [19]. However, some scientists have reported that the highest NH_3 volatilization rates for major crops occur during the reproductive growth stage [20]. A large quantity of nitrogen accumulates in seeds of cereals and legumes; this nitrogen is not recycled and is lost from the soil-plant system. Fageria *et al*. [8] reported that about 50% of the total nitrogen accumulated was in the grains of upland rice cultivars and the remaining 50% was in the roots and shoots.

Knowledge of nutrient cycling in soil-plant systems is fundamental to an understanding of nutrient availability and the loss of nutrient balance to crop plants, beginning with sources of phosphorus (P) in soils. Unlike N, which can be returned to the soil by fixation from the air, P cannot be replenished except external sources once it leaves the soil in agricultural products or by erosion. Origins of P in soils include residual soil minerals or inputs of P from commercial fertilizers and organic manures. Hence, both organic and inorganic sources of P are found in soil-plant systems and both are important P sources for plants. However, only a small fraction of the total P is in a form available to plants. Inorganic forms of P are mainly calcium and iron or aluminum bounded. Calcium-bounded P predominates in alkaline soils and iron- and aluminum-bound P predominates in acidic soils. The organic fraction of P varies from soil to soil and may constitute 20 to 80% of the total P of the surface soil horizons [21]. Organic P should be mineralized before it is taken up by plants. Solubilization and immobilization are the main transformation processes of P in the soil-plant systems that control its availability to plants and potential losses. Immobilization or fixation is defined as the strong adsorption or precipitation of P ions on aluminum (Al) and iron (Fe) hydroxides. Soil erosion, surface and subsurface runoff, leaching and uptake by plants are the main avenues of P loss in soil-plant systems.

The recovery efficiency of applied soluble P fertilizers by annual crops during their growth cycle is less than 20% in most of the acid soils [22, 23]. P uptake by plants mainly occurs in the form of $H_2PO_4^-$ ion in acid soils and the form of HPO_4^{2-} ion in basic or alkaline soils. The proportion of these two ions in the soil solution is governed by pH. At pH 5, most of P is in the form of $H_2PO_4^-$ and at pH 7, both of these ions are present more or less in equal amounts [24]. The uptake of P by plants is governed by the ability of a soil to supply P to plant roots and by the desorption characteristics of the soil [23]. In acid soils, P is mainly immobilized or fixed by Al and Fe ions; moreover, in basic or alkaline soils, P immobilization or fixation takes place by the following reactions:

Al^{3+} + $H_2PO_4^-$ (soluble) + $2H_2O$ ◎ Al (OH) $2H_2PO_4$ (insoluble) + $2H^+$

Fe^{3+} + $H_2PO_4^-$ (soluble) + $2H_2O$ ◎ Fe (OH) $2H_2PO_4$ (insoluble) + $2H^+$

Ca $(H_2PO_4)_2$ (soluble) + $2Ca^{2+}$ ◎ Ca_3 $(PO_4)_2$ (insoluble) + $4H^+$

P immobilization is high in soils containing a higher amount of amorphous Fe and Al hydroxides and allophane. This complexion reduces ion mobility and renders a large proportion of the total inorganic P insoluble and unavailable to plants. Thus, P acquisition is not a problem of total supply but unavailability caused by the extreme insolubility of P at both acidic and alkaline pH. As a result, concentrations of P in the soil solution are often low for adequate plant nutrition [25]. P recovery increased with increasing levels of P. The P immobilization is higher in soils containing high clay content compared with coarse-textured soils. Fageria and Gheyi [17] reported that in Oxisols and Ultisols of the tropics, P immobilization capacity is high. These authors recommend that in these soils, soluble P should not be applied in anticipation of sowing crops. Because most crops need P throughout their growth cycle, if P is applied in advance, a large part of it may be fixed in the beginning and crops may suffer from P deficiency.

Potassium (K), like N, is not easily lost from soil-plant systems and, unlike P, is not immobilized in the soil. The main K^+ addition sources for plant growth are chemical fertilizers, crop residues, organic manures and K^+ bearing minerals. The main K^+ depletion sources in the soil are removal by crops, leaching losses, erosion and runoff losses and immobilization by microorganisms or soil colloids. K fertilizer losses by leaching are minor, except in very sandy soils. A major part of K^+ depletion in soil-plant systems is due to losses by erosion and runoff and uptake by crops. The majority of K^+ moves to plant roots by diffusion. This diffusion process is dependent on several factors including the soil water content, tortuosity of the diffusion path, temperature, diffusion coefficient of K^+ in water and the K^+ concentration gradient, particularly if a depletion zone exists around the absorbing roots [26]. Nonexchangeable K^+ and mineral K^+ are the major K^+ forms in the soil-plant system. K^+ move from one category to another whenever the removal or addition of K^+ disturbs the equilibrium within this soil K^+ pool [23]. The ability of a soil to replenish solution K^+ is dependent on the transformations between the various labile K^+ forms and the nature of their respective equilibrium with the soil solution [26]. K fixation by clay decreases leaching susceptibility and luxury uptake by crop plants. The leaching of K^+ is determined by the amount of rainfall and soil types. Light-textured soils are more prone to K^+ leaching compared to heavy-textured soils. This may be due to the low cation exchange capacity of light-textured or sandy soil. K uptake during plant growth is a dynamic process with periods of K^+ depletion in the root zones and release of non-exchangeable K^+ to exchangeable and solution factions by K^+ bearing soil minerals. This process does not result in significant disintegration of the mineral matrix, which can occur with some laboratory methods used to determine nonexchangeable K+ supply [27].

The processes of removal and addition regulate the calcium (Ca) cycle in soil-plant systems. Ca is mostly removed or lost from soil-plant systems by leaching, soil erosion and crop removal. It is also adsorbed on soil colloids under specific conditions. Under acid conditions, Ca^{2+} ion is displaced by Al^{3+} and H^+ ions from the exchange complex and leaching of this element may occur. The Ca^{2+} content of soil depends on its parent material, degree of weathering and whether liming and fertilizers have added Ca. A large amount of Ca^{2+} in the soil is present as exchangeable Ca^{2+}, which depends on the cation exchange capacity of a soil. The concentration of soil solution Ca^{2+} is determined by cation exchange capacity (CEC), the nature of the bonding with exchange sites, pH, type of soil and the level of anions in solution. Exchangeable Ca^{2+} is more tightly held on soil colloids than either K^+ or Mg^{2+}. Ca also be present in soil minerals having varying degrees of solubility. Solution and exchangeable Ca are the main forms that can move to the plant root and be absorbed [28]. Gypsum and Ca carbonate are soil minerals having greater solubility and higher Ca content. Mass flow is generally the primary mechanism for supplying Ca plant roots for absorption. As the soil pH increases, adsorption of Ca and Mg increases, especially in soils rich in iron and aluminum oxides. The pH in these situations acts in two ways in determining the adsorption of Ca and Mg by soils with variable charge. One way is by increasing the negative charge of the soil and providing an increased number of exchangeable sites with a higher affinity for divalent cations. The other way is to increase the population of hydrolyzed divalent cations as $Ca^{2+} + OH^- \rightleftharpoons CaOH^+$, which can then become specifically adsorbed into the stem layer [29]. At pH < 6, most of the adsorbed Ca remains exchangeable, but as the pH is increased, more divalent cations become specifically adsorbed and therefore are no longer exchangeable [30].

The cycle of magnesium (Mg) in soil-plant systems involves its addition to soils and depletion by several processes. The main sources of Mg^{2+} addition are liming, Mg^{2+} fertilizers, crop residues, farmyard or green manures and liberation by weathering of parent materials. Its removal or depletion from the soil-plant system is mainly through uptake by crops, soil erosion and leaching. Besides, some part of Mg^{2+} is also fixed in the soil-plant system by soil colloids and microorganisms. Most of the Mg^{2+} is present in the soil as primary minerals and very little exists in organic forms or the form of organic complexes. The addition of Ca^{2+} increases the leaching of Mg^{2+} from the soil profile because Ca^{2+} is held more tightly on to soil colloids compared to Mg^{2+}. Under acidic conditions, Al^{3+} and H^+ ions displace Mg^{2+} from the exchange complex and leaching may occur. The affinity of cations for the exchange complex is dependent on the mineralogy of the colloids. For instance, the affinities of Ca^{2+} and Mg^{2+} for montmorillonite are similar, but the affinity of Mg^{2+} for vermiculite is much greater than the affinity of Ca^{2+} [31]. The fractions of Mg^{2+} in the soil are classified as non-exchangeable, exchangeable and water-soluble or in soil solution. These three Mg forms are in equilibrium and the non-exchangeable form is maximized compared to the other two forms. Some Mg^{2+} presents in the soil in association with organic matter, but this fraction is usually less than 1% of the total soil Mg^{2+} [24]. The transport of Mg^{2+} to the root of plants mainly occurs by mass flow and diffusion.

Sulfur (S) is absorbed by plants and immobilized by microorganisms and moves in soil-plant systems like N. S, an essential element for microorganisms and plants is continuously being cycled between inorganic and organic forms [32]. The principal sources of S addition to soil are chemical amendments or fertilizers, farmyard manure, or crop residues. Besides, gaseous forms of hydrogen sulfide (H_2S) and S dioxide (SO_2) are released to the atmosphere by the burning of fossil fuels and are deposited in the soil by rain. The important depletion sources of S from the soil is uptake by crop plants, loss through erosion, surface runoff, leaching and immobilization by soil microbial activities and adsorption by soil colloids. The adsorption is by ligand exchange with surface hydroxyl groups by which sulfate replaces OH^- coordinated to Fe^{3+} or Al^{3+} to form a covalent bond with the surface [24]. The sulfate adsorption capacity of soil colloids depends on soil pH and decreases as soil pH increases. The immobilization of S in the soil-plant system is controlled by the C/S ratio of the organic matter or residues. S is present in soils in both organic and inorganic forms. However, the organic form is dominant in most agricultural soils. The organic forms of S must be mineralized by soil organisms if the S is to be utilized by plants. The sulfate ion (SO_4^{2-}) has a negative charge, can move easily with soil water and is readily leached from sandy soils under conditions of high rainfall. Very little SO_4^{2-} is adsorbed in the A horizon of these soils because of their low content of hydrated oxides of Fe^{3+} and Al^{3+}, high available P and limed status [33]. Factors affecting SO_4^{2-} adsorption includes pH, type of cation present, presence of competing anions, extractable Al^{3+} and Fe^{3+} fractions, extractable SO_4^{2-}, organic C, clay content and soil horizon type. The amount of SO_4^{2-} retained or adsorbed by soil increases with clay content. Retention of SO_4^{2-} decreases as the pH increases and adsorption appears to be negligible in many soils when pH is above 6.5 [34]. The elemental S is oxidized by the bacteria and hence, S oxidation produces soil acidity and in alkaline soils, S is used as an amendment for reclamation. However, elemental S is not recommended in acid soils as a source of S fertilizer due to high acidity production by oxidation.

Nutrient Functions and Deficiency Symptoms: The functions and deficiency symptoms of nutrients are indicated in Tables 5 and 6. N has a greater influence on the growth and yield of crop plants than any other essential plant nutrient. It plays a pivotal role in many physiological and biochemical processes in plants. N is a component of many important organic compounds ranging from proteins to nucleic acids. It is a constituent of the chlorophyll molecule, which plays an important role in plant photosynthesis. Many enzymes are proteinaceous; hence, N plays a key role in many metabolic reactions. N is also a structural constituent of cell walls. A shortage of N restricts the growth of all plant organs, roots, stems, leaves, flowers and fruits (including seeds). The N-deficient plant appears stunted because of the restricted growth of the vegetative organs. N is a mobile nutrient in plants and its deficiency symptoms first appear in the lower or older leaves. The N deficiency symptoms first start in the tips and margins of the leaves. In cases of severe deficiency, the whole leaf becomes yellow and dry. In legumes, N deficient leaves may fall off. N deficient plants grow slowly and their leaves are small. N deficiency also decreases leaf area index, lowers radiation use efficiency and lowers photosynthesis activity in plants [15, 35]. Seeds are small and yields are reduced in cereals and legume crops under N deficient conditions. The reduction in yield and quality are directly related to the severity of the N deficiency. Moreover, N deficiency symptoms are associated with reduced plant height, tillering in cereals, pods in legumes, leaf discoloration and reduced growth of newly emerging plant parts. N deficiency also reduces root growth, which negatively influences the absorption of water and nutrients by plants. N deficient plants have fewer root hairs compared to plants supplied with adequate amounts of N [36].

Sometimes under conditions of the sufficiency of N, leaves, especially the lower ones, will provide N to fruits and seeds and symptoms of deficiency may develop on the leaves. These symptoms, which develop late in the growing season, may not be evidence of yield-limiting deficiencies but are expressions of transport of N from old leaves to other portions of the plant [37-39]. Observation of nitrogen deficiency symptoms in crop plants is the cheapest method of diagnosis for N disorders. However, this technique requires a lot of experience on the part of the observer, because deficiency symptoms can be confused with problems caused by drought, insect and disease infestation, herbicide damage, soil salinity, soil acidity and inadequate drainage [40]. Sometimes, a plant may be on the borderline to deficiency and adequacy of a given nutrient. In this situation, there are no visual symptoms, but the plant is not producing at its capacity. This condition is frequently called "hidden hunger." Deficiency symptoms normally occur over an area and not on an individual plant. If a symptom is found on a single plant, it may be due to disease or insect injury, or a genetic variation [40]. Mineral-deficient plants are usually more susceptible to diseases, insects and physical damage [41].

P is essential for plant growth and reproduction and is a major nutrient along with N and K. Its functions cannot be performed by any other nutrients. Without an adequate supply of P, a plant cannot reach its maximum yield potential [17]. P plays an important role in energy storage and transfer in crop plants. Adenosine diphosphate (ADP) and adenosine triphosphate (ATP), summarized through both respiration and photosynthesis, are compounds with high-energy phosphate groups that drive most physiological processes in plants including photosynthesis, respiration, protein-nucleic acid synthesis and ion transport across cell membranes [42, 43]. In cereals, P increases tillering; in legumes,

Table 5: Summary of functions of essential macronutrients in plants

Element	Functions in plant
Nitrogen	Found in chlorophyll, nucleic acids and amino acids. Component of protein and enzymes, which control almost all biological processes
Phosphorus	Typically concentrated in the seeds of many plants as phytin. Important for plant development including development of a healthy root system, normal seed development, uniform crop maturation, photosynthesis, respiration, cell division and other processes and, essential component of Adenosine Triphosphate (ATP). An essential component of DNA and RNA and phospholipids
Potassium	Responsible for the regulation of water usage in plants, disease resistance and, stem strength. Involved in photosynthesis, drought tolerance, improved winter-hardiness and, protein synthesis. Linked to the improvement of overall crop quality, including handling and storage quality
Calcium	Essential for cell elongation and division. Specifically required for root and leaf development, function and cell membranes and, the formation of cell wall compounds. Involved in the activation of several plant enzymes
Magnesium	The primary component of chlorophyll and is therefore actively involved in photosynthesis. The structural component of ribosomes, which are required for protein synthesis. Involved in phosphate metabolism, respiration and the activation of several enzyme systems.
Sulfur	Required for the synthesis of the sulfur-containing amino acids (cysteine and methionine), which are essential for protein formation. Involved with the development of enzymes and vitamins, promotion of nodulation for N fixation by legumes, seed production, chlorophyll formation and, the formation of several organic compounds that give characteristic odors to garlic, mustard and onion.

branches increased with P fertilization. Root development increases with P fertilization in cereals as well as legume crops [44]. P strengthens culm strength in plants and hence prevents lodging. Crop quality in forages and vegetables is also improved with P fertilization. The formation of seeds and fruits is especially depressed in plants suffering from P deficiency. Thus, not only yields but also poor-quality seeds and fruits are obtained from P-deficient plants [24]. P is needed in especially large amounts in meristematic tissue, where cells are rapidly dividing and enlarging [21]. P is also a key component of Phytin, a seed component that is essential to inducing germination.

P deficiency can reduce seed size, seed numbers and viability. P nutrition has been related to all facets of N_2 fixation in leguminous plants, probably due to the relationship between P and energy transfer mechanisms. Leaf area, leaf numbers and leaf expansion decreased under P stress [45-47]. Low P decreased shoot branching in bean [45] and an increase in root-to-shoot ratio was often observed [45, 48]. P is a mobile nutrient in the plant; hence, P deficiency symptoms first appear on the older leaves. The visual symptoms of a P shortage, apart from stunted growth and reduced yields, are purple or reddish color on the older leaves. P is not a constituent of chlorophyll; thus, in P-deficient plants, the concentration of chlorophyll in a leaf becomes comparatively high and the color of leaves, especially younger ones, changes to dark green [17]. P deficiency symptoms in plants include severe stunting, thin stems and erect and dark green leaves. P deficiency reduces seedling height, tiller number, stem diameter, leaf size and leaf duration [23]. When P is deficient, cell and leaf expansions are retarded more than chlorophyll formation. Thus, the chlorophyll content per unit leaf area increases, but the photosynthetic efficiency per unit of chlorophyll decreases [49].

Functions of K to increase crop yields can be summarized as follows [17]: K^+ increases root growth and improves water and nutrient uptake, builds cellulose and reduces lodging, required to activate at least 60 different enzymes involved in plant growth, reduces respiration, preventing energy losses, aids in photosynthesis and food formation, helps translocation of sugars and starch, produces grain rich in starch, increases the protein content of plants, maintains turgor and reduces water loss and wilting, helps retard crop diseases, Although K^+ is not a constituent of chlorophyll, a characteristic symptom of K^+ deficiency is the destruction of chlorophyll, deficiency can inhibit N fixation by reducing plant growth in legumes, neutralizes acids produced during metabolism of carbohydrates in the plant cell, intimately involved in the opening and closing of stomata, implicated in increased uptake and transport of Fe in both monocotyledonous and dicotyledonous plants and not only can K^+ increase the resistance of plant tissues, but it may also reduce fungal populations in the soil, reduce their pathogenicity and promote more rapid healing of injuries [50]. K, like N and P, is highly mobile in plant tissues. Hence, K^+ deficiency symptoms first appear in the older leaves. K deficiency symptoms show up as scorching along leaf margins of older leaves. K-deficient plants grow slowly. They have poorly developed root systems. Stalks are weak and lodging is common. Seed and fruit are small and shriveled and plants possess low disease resistance. Plants under stress from short K^+ supplies are very susceptible to unfavorable weather. Although it cannot be detected as it is happening, stand loss in forage grasses and legumes is a direct result of K^+ deficiency. In grass/legume pastures, the grass crowds out the legume when the K^+ runs short because the grass has a greater capacity to absorb K and the legume is starved out.

Ca is involved in cell division and cell elongation and plays a major role in the maintenance of cell membrane integrity [8]. Besides, Ca plays an important role in maintaining nutrient balance in plant tissues and also ameliorates the toxicity of heavy metals. Plant cells without Ca^{2+} tend to lose their semi permeability and collapse. Ca has been found to catalyze some enzymes involved in the hydrolysis of adenosine triphosphate (ATP) and phospholipids and to partially replace Mg^{2+} in some reactions. Root growth is severely restricted in Ca^{2+} deficient plants and the roots become prone to infection by bacteria and fungi. Ca protects the plasma membrane from the deleterious effects of H^+ ions at lower pH and also reduces the harmful effects of Na^+ in salt-affected soils [51]. Many biotic and abiotic stresses are reduced by the presence of adequate amounts of Ca in the rhizosphere [52]. The role of Ca^{2+} in the regulation of the stomata aperture is also elucidated by Schroeder *et al.* [53] and Epstein and Bloom [51]. Ca acts as a regulator ion in the translocation of carbohydrates through its effect on cells and cell walls [54]. Ca is cited for its beneficial effect on plant vigor and stiffness of straw and also on grain and seed formation [55]. The low supply of Ca inhibits the nodulation, growth and N fixation of bacteria associated with the root of legumes [56]. Ca is considered to be essential for the germination of pollen and the growth of the pollen tube in plants [17].

Very little Ca^{2+} accumulates in the seeds of most crop plants. Hence, the Ca^{2+} requirements of crop plants are met by the addition of this element in the soil-plant system. Ca is immobile in plants and Ca^{2+} deficiency appears first in the newly emerging leaves or forming tissues. Even with the Ca^{2+} deficiency of new leaves, the older or lower leaves may contain sufficient amounts of Ca^{2+}. Ca deficiency is characterized by dead and tightly curled leaf tips that are usually bent over and sticky or gummy to the touch [41]. Plants with severe Ca^{2+} deficiency are stunted since internodes fail to elongate and the new growth grows in a rosette form. Leaf tips fail to unfold, are deformed and form sword-like projections. Leaves become brittle, frequently coalesce, turn brown and form sticky vehicles at or near the margins. Shoot–root ratios usually decrease because shoots are affected more extensively than roots [57]. Root tips turn brownish, root extension is inhibited, lateral branching is reduced and taproots are small in diameter [58]. Flowering and maturity are delayed by mild Ca deficiency, but ear or head size is often unaffected in cereals. However, when Ca deficiency is severe, the head may not form or it may be partly barren [59]. New tissue needs Ca^{2+} pectate for cell wall formation.

Mg is a mineral constituent of plant chlorophyll, so it is actively involved in photosynthesis. Mg also aids in phosphate metabolism, plant respiration and the activation of several enzyme systems involved in energy metabolism [17]. Mg aids in the formation of sugars, oils and fats. It also activates the formation of polypeptide chains from amino acids [60]. Mg is also an essential element for microbial growth and is implicated in microbial ecology in early studies of soil microbiology since Mg carbonate applied to certain soils increases the reproduction of soil bacteria [61]. It is associated with rapid growth, active mitosis, high protein levels, carbohydrate metabolism and oxidative phosphorylation in physiological young cells [61]. Mg is a mobile element in the plant and deficiency symptoms of this element first appear in the older leaves and tissues. Symptoms of Mg^{2+} deficiency are characterized by a light coloring between the veins or interveinal chlorosis. Leaves became brittle and margins curled. Dark necrotic spots appear and leaves usually turn reddish-purple with a severe deficiency; the tips and edges may die as Mg is translocated from old to new plant tissue [41]. Root growth is reduced in Mg deficient plants and Mg deficient plants' roots turn dark red [62]. Height and tiller number are little affected in cereals when the deficiency is moderate [17]. Mg deficient plants lack vigor, are often stunted and usually have a delayed reproductive stage [57]. Shoot–root ratios increase with Mg deficiency because root growth decreases more than shoot growth [57]. Mg deficiency also inhibits N_2 fixation by N-fixing rhizobium bacteria. Mg deficiency can occur after heavy application of ammonia or K fertilization [63]. Seldom is an excess of Mg directly harmful to the plant, but excess may suppress the uptake of Ca, K and manganese (Mn) and reduce plant growth [61].

S plays many important roles in the growth and development of plants. Fageria and Gheyi [17] summarized the important functions of the sulfur in the plant: S is an important component of two amino acids, cysteine and methionine, which are essential for protein formation. Since animals cannot reduce sulfate, plants play a vital role in supplying essential S-containing amino acids to them [64], it plays an important role in enzyme activation, it promotes nodule formation in legumes, S is necessary in chlorophyll formation, although it is not a constituent of chlorophyll, the maturity of seeds and fruits is delayed in the absence of adequate S, S is required by plants in the formation of nitrogenase, it increases crude protein content of forages, it improves quality of cereal crop for milling and baking, it increases oil content of oilseed crops, it increases winter hardiness in plants, it increases

Table 6: Summary of deficiency symptoms and occurrence of macronutrients in plants

Element	Mobility	Deficiency symptoms and occurrence
Nitrogen	Mobile within plants: lower leaves show chlorosis first.	Stunted, slow-growing, chlorotic plants. Reduced yield. Plants more susceptible to weather stress and disease. Some crops may mature earlier. N deficiency can be confused with those of S deficiency.
Phosphorus	Mobile within plants: lower leaves show deficiency first.	Over-all stunted plant and a poorly developed root system. Can cause purple or reddish color. Leaves are narrow, short and, very erect. The number of leaves, panicles and grains per panicle is also reduced. Delayed maturity.
Potassium	Mobile within plants: lower leaves show deficiency first.	Commonly causes scorching or firing along leaf margins. Plants grow slowly, have poorly-developed root systems, weak stalks; lodging is common. Seed and fruit are small and shriveled. Plants possess low disease resistance. Deficiencies most common on acid sandy soils and soils that have received large applications of Ca and/or Mg.
Calcium	Not mobile within plants: upper leaves and the growing point show deficiency symptoms first.	Poor root growth. Ca deficient roots often turn black and rot. The tips of the youngest leaves become white (bleached), rolled and curled. Necrotic tissue may develop along the lateral margins of leaves. Most often occurs on acid soils where Ca levels are low. Ca deficiency resembles B deficiency?
Magnesium	Mobile within plants: lower leaves show deficiency first.	Leaves show a yellowish, bronze, or reddish color while leaf veins remain green. Plants are pale-colored, with Interveinal chlorosis first appearing on older leaves and later on younger leaves. Reduced number of spikelets and reduced 1000-grain weight. Reduced grain quality.
Sulfur	Somewhat mobile within plants but upper leaves tend to show deficiency first.	Leaves show a yellowish, bronze, or reddish color while leaf veins remain green. Reduced plant height and stunted growth. Reduced number of tillers. Plant development and maturity are delayed.

drought tolerance in plants, it controls certain soil borne diseases, it helps in formation of glucosides that give characteristic odors and flavors to onion, garlic and mustard, S is necessary for the formation of vitamins and synthesis of some hormones, it is involved in oxidation-reduction reactions, S improves tolerance to heavy metal toxicity in plants, it is a component of S-containing sulfolipids, organic sulfates may serve to enhance water solubility of organic compounds, which may be important in dealing with salinity stress [65] and fertilization with soil-applied S in sulfate form decreases fungal diseases in crops [66, 67]. S deficiency symptoms are often observed in crops at the early stages of growth since S can be easily leached from the surface soil [68]. S deficiency symptoms are similar to those of N. However, N deficiency symptoms first appear in the older leaves; generally, S deficiency symptoms first appear in the younger leaves because S is not easily translocated in the plant. S-deficient plants lack vigor, are stunted, are pale green to yellow and have elongated thin stems. S deficiency may delay maturity in grain crops. Interveinal chlorosis may occur. Root development is restricted and shoot–root ratios usually decrease for plants grown under S deficiency [57].

Nutrient Uptake and Use Efficiency: Uptake of nutrients by crop plants in adequate amount and proportion is very important for producing higher yields. Similarly, the distribution of absorbed or accumulated nutrients in shoot and grain (higher N in grain) is associated with yield improvement [15]. Nutrient uptake in crop plants is mainly measured by tissue analysis. Nutrient concentration in plant tissue varied with plant tissue analyzed (leaves, shoot, or whole plant), plant age, dry matter or grain yield level, crop species or genotypes within species, crop management practices and environmental factors [36, 40, 69]. Plants have a remarkable ability to regulate nutrient uptake according to their growth demands [15]. Significant variation in nutrient concentrations in the growth medium did produce very small changes in nutrient concentration in plant tissue [15]. Hence, it can be concluded that concentrations of most nutrients in plant tissues are restricted to fairly narrow ranges [15]. Concentration is used to diagnose nutrient deficiency, sufficiency, or toxicity in crop plants. Critical nutrient concentration is usually designated as a single point within the bend of the crop-yield–nutrient-concentration curve where the plant nutrient status shifts from deficient to adequate. N concentration in shoot and grain of cereal and legume reveal the change in concentration of this nutrient. Because plant age is one of the most important factors affecting nutrient concentrations in plant tissue, N concentration in both the crop species decreased significantly in a quadratic fashion with the advancement of plant age, indicating necessary to perform plant tissue analysis at different growth stages. The concentration of N is higher in the grain than in the shoot at harvest, indicating translocation of N from shoot to the grain in cereals as well as in legumes. During grain filling, the N content of non-grain tissue generally decreases while grain N content increases [70]. However, shoot dry weight increased with age advancement up to the flowering growth stage and then decreased [23]. A decrease in shoot dry weight at harvest is related to translocation of assimilates to the panicle from flowering to maturity [8]. On a physiological basis, critical leaf nutrient levels indicate the minimum amount of cell nutrient concentration that allows for the maintenance of metabolic functions at non limiting growth rates [71]. N uptake values varied among crop species and are higher in grain than in straw. This indicates that grains are greater sinks for N accumulation compared with other aboveground parts. A higher nitrogen harvest index (NHI) in crop plants or genotypes is desirable because it has a positive association with grain yield. Generally, NHI values are higher in legumes than in cereals [70].

The P use efficiency (PUE) can be defined as the maximum economic yield produced per unit of P applied or absorbed by the plant. Tissue analysis is an important technique for diagnosing nutritional disorders in crop plants. Nutrient concentration in plant tissue varied with plant age. As a general rule, the nutrient concentration decreased with the advancement of plant age. The decrease in nutrient concentration with the advancement of plant age is associated with increased dry matter yield. The decrease in nutrient concentration with the advancement of plant age is known as the dilution effect in the mineral nutrition of plants. Plants do not require as much P as they do N and K. P uptake by plants is influenced by climatic, plant and soil factors. The important climatic factors that control P availability to plants are soil temperature, moisture content and solar radiation. The important soil factors controlling P availability are the concentration of P in the soil solution, soil texture, organic matter content and soil pH, presence of other essential nutrients in quantity and proportion and microbial activities. Plant species and genotypes within species also influence P uptake. The quantity of P removed by a crop depends on yield level, fertility level and other management practices. However, after fixation, a large part of the P is removed from the soil-plant system in harvesting parts of the plants. Hence, it can be concluded that P requirements are higher for grain compared to shoot in the cereals as well as in the legumes. The grain harvest index and P harvest index are higher for legumes compared to cereals. This means that P requirements are higher for legumes compared to cereals.

The majority of K^+ is accumulated in the shoot of cereals like rice and corn and a small amount is translocated to the grain. Hence, the incorporation of cereal straw into the soil may have a significant effect on the recycling of K^+ in soil-plant systems. In dry beans, about 60% of the total K^+ accumulated was translocated to grain and 40% remained in the shoot. In soybean, 50% of the accumulated K^+ was translocated to grain and 50% remained in the shoot. Overall, cereals accumulated more K^+ in shoot compared to legumes. This was associated with a higher shoot yield of cereals compared to legumes. The higher K^+ content of grain legumes compared to cereals mirrors the special importance of legumes in human nutrition. Grain harvest index (GHI) and K harvest index (KHI) are important indices in the determination of crop yields and K distribution in plants, respectively. These two indices are influenced by K fertilization. The GHI reflects the partitioning of photosynthate between the grain and the vegetative plant part and improvements in GHI emphasize the importance of carbon allocation in grain production [36]. Snyder and Carlson [72] reviewed the relation of GHI to grain yield in legumes and cereals and reported that GHI correlated positively with grain yield. Fageria *et al*. [73] also found a significant and positive correlation between grain yield and grain harvest index in dry beans. Nutrient absorption and nutrient use efficiency of a crop species or variety are important aspects for the improvement of crop yield and the reduction of production costs [23]. The higher K use efficiency in cereals is associated with a lower accumulation of K^+ in the grain of cereals compared to legumes. Fageria *et al*. [23] reported that K^+ apparent recovery efficiency (ARE) in lowland rice genotypes ranged from 51 to 81% and varied among lowland rice genotypes. In addition to recovery efficiency, agronomic efficiency (AE), defined as grain yield obtained with the application of per unit nutrient, is an important index in determining crop yields. Fageria *et al*. [23] reported that AE in lowland rice varied from 44 to 80 kg kg^{-1}, with an average value of 66 kg kg^{-1}. Fageria [74] reported a significant positive association of AE and ARE with grain yield of upland rice genotypes. This means that improving potassium use efficiency in crop plants can improve their yields.

Ca concentration (uptake per unit dry weight) in plant tissues is an important parameter for the diagnosis of deficiency or sufficiency level in crop plants. The Ca^{2+} concentration in plant tissues varied with soil, climatic and plant factors. Among plant factors, age and part of tissue analyzed are the most important in determining Ca concentration. Higher Ca^{2+} requirements of legumes compared to cereals have been widely reported [8, 28]. Ca uptake (concentration × shoot or grain dry weight) is an important index for measuring soil fertility depletion with the cultivation of crop plants. The uptake of Ca^{2+} depends on the dry weight of shoot and grain yield and varied from crop species to crop species. The Ca^{2+} uptake is higher in shoot compared to the grain in cereals as well as legume crops. Besides, it is higher in the grain of legumes compared to the grain of cereals. Hence, a higher quantity of Ca is required by legumes compared to cereals to produce similar amounts of economic yield. Ca use efficiency, which is defined as straw or grain yield per unit of Ca uptake in straw and grain, varies with crop species. It is higher for the production of a grain of cereals as well as legumes compared to shoot of cereals or legumes. The higher Ca efficiency for grain production of cereals and legumes compared to shoot is associated with lower amounts of Ca accumulation in the grain, as indicated by the Ca harvest index values of crops. Generally, legume seeds have higher Ca content compared to cereals and this has special significance for human nutrition.

Soil solution concentration of Mg^{2+} is higher than that of K^+, but the uptake rate of this element is lower than that of K^+. The uptake rate of Mg^{2+} and K^+ by rice plants is influenced by Ca^{2+} concentration in the nutrient solution. The absorption rate of Mg^{2+} is much lower compared to K^+ at a given Ca^{2+} concentration. Uptake of Mg^{2+} as well as K^+ is significantly influenced by Ca^{2+} concentration in the growth medium. The higher uptake rate of monovalent cations like K^+ compared to divalent cations like Mg^{2+} and Ca^{2+} has been widely reported in the literature [75, 76]. The reason for the high uptake rate of monovalent cations compared to divalent cations may be hydrated ion size. Berry and Ulrich [77] reported that a higher uptake rate of K compared to Ca and Mg is associated with very efficient and selective K mechanisms of higher plants. The Mg uptake is higher in the shoot compared to the grain in the cereals as well as in legumes. In the cereals, Mg uptake in shoot plus grain varied from 11 to 30 kg ha^{-1} depending on crop species. Crops remove from 10 to 80 kg Mg ha^{-1} depending on the yield and the particular crop [78]. The variation in uptake of Mg^{2+} by shoot and grain of different crops is also associated with variation in yield of shoot and grain of these crops [79-81]. Overall, Mg^{2+} use efficiency in the shoot, as well as grain, is higher in cereals compared to legumes. The higher Mg use efficiency in cereals compared to legumes is associated with low amounts of Mg accumulated in upland rice and corn compared to dry bean and soybean. It is well known that dicotyledons generally have higher contents of divalent cations than monocotyledons; the reverse holds for monovalent cations [82]. Overall, the Mg^{2+} harvest index is higher in legumes than in cereals. This means that the Mg^{2+} requirement of legumes is higher compared to cereals. This means that Mg^{2+} accumulation in grain of cereals and legumes does not affect grain yield.

S concentration in plant tissues is an important criterion for identifying its deficiency or sufficiency in crop plants. Nutrient concentration including S varied with plant age and plant part analyzed. It decreased in crop tissues over time [83]. Brady and Weil [21] reported that healthy plant foliage generally contains 1.5 to 4.5 g kg^{-1} sulfur (0.15 to 0.45%). The uptake of S depends on the rate at which it is released from organic matter, which in turn is influenced by the kinds of plant residues, soil moisture and soil pH [63]. S can also be absorbed by the leaves through the stomata as a gaseous sulfur dioxide (SO_2), an environmental pollutant released primarily from burning coal and fossil fuel [84]. S absorbed by roots is translocated to leaves through the xylem and is reduced and assimilated into organic compounds predominantly in the leaf blades [85]. The S uptake in the shoot varied from 3 to 20 kg ha^{-1}, depending on crop species and yield of each species. Similarly, S uptake in grain varied from 3 to 25 kg ha^{-1}, with an average value of 10.6 kg ha^{-1}. Total uptake of S (shoot plus grain) varied from 6 to 43 kg ha^{-1}, with an average value of 22 kg ha^{-1}. Among crop species, corn accumulated maximum S and flax minimum. The maximum and minimum values of S uptake are associated with the yield of these crop species. Overall, cereals have higher S use efficiency for grain production compared to legumes or oil crops, indicating higher S requirements for legumes compared to cereals. The S harvest index varied from 26% in wheat to 67% in buckwheat, with an average value of 48% in 12 crop species. Hence, it can be concluded that about 52% of S is retained in the straw of annual crops and if it is incorporated into the soil after harvest of these crops, a significant amount of S can be recycled to maintain soil fertility. Apparent sulfur recovery efficiency (ASRE) is higher at lower S rate and decreased with increasing S rate in the range 25 to 100 kg S ha^{-1}. Immobilization, leaching of SO_4^{2-} and reduction to sulfide forming less soluble compounds in flooded rice might be responsible for low S use efficiency by lowland rice [86].

Interaction with Other Nutrients: Balanced supply of essential nutrients is one of the most important factors in increasing yields of annual crops. Hence, knowledge of the interaction of N with other nutrients is an important factor in improving the efficiency of this element and consequently improving crop yields. Nutrient interaction in crop plants is measured in terms of uptake or yield level. Application of a particular nutrient may increase, decrease, or have no effect on the uptake of other essential plant nutrients. Similarly, the yield level of a crop may increase, decrease, or experience no change with the increase of two nutrient levels in the growth medium. Hence, nutrient interactions may be positive, negative, or neutral. In mineral nutrition, the nutrient interactions are designated as synergistic (positive), antagonistic (negative), or neutral. Nutrient interaction can occur at the root surface or within the plant. Interactions at the root surface area due to the formation of chemical bonds by ions and precipitation or complexes. One example of this type of interaction is the liming of acid soil, which decreases the concentration of almost all micronutrients except molybdenum [87, 88]. The second type of interaction takes place between ions whose chemical properties are sufficiently similar that they compete for sites of absorption, transport and function on the plant root surface or within plant tissues. Such interactions are more common between nutrients of similar size, charge and geometry of coordination and electronic configuration [89].

The ratio of the mass of organic carbon, to the mass of organic nitrogen in the soil, known as the C/N ratio, controls N availability. A C/N ratio >30/1 generally immobilizes N in soil-plant systems and creates the possibility of N deficiency in crop plants [90]. N has positive interactions with P and K in crop plants. Wilkinson *et al*. [91] reported that application of N increased uptake of P, K, S, Ca and Mg provided that these elements are present in sufficient amounts in the growth medium. The improvement in uptake of macronutrients with the addition of N is reported to be associated with an increase in root hairs, chemical changes in the rhizosphere and physiological changes stimulated by N, which influence the transport of these elements [22, 49]. Rapid nitrate uptake depends on adequate K in the soil solution. Higher rates of K allowed for the efficient use of more N, which resulted in better early vegetative growth and higher grain and straw yield as K and N rates increased. In the field, better N uptake and utilization with adequate K means improved N use and higher yields. Crops need more K with higher N rates to take advantage of the extra N [17]. N interactions with micronutrients depend on pH changes in the rhizosphere. If N is absorbed in the form of NH_4^+, rhizosphere pH may decrease and uptake of most micronutrients increases. If N is mainly absorbed as NO_3^-, rhizosphere pH may increase and uptake of most micronutrients decreases. An increase in crop growth with the application of N may increase crop demands for micronutrients and micronutrient deficiencies may occur [91]. Zinc deficiency in upland rice and corn in Brazilian Oxisols is very common and the response of these crop plants to N fertilization is one reason for such deficiency [17]. Chlorine decreases NO_3^- uptake and enhances the uptake of NH_4^+ [92]. These authors also reported that ammonium increases the uptake of Mn.

P has positive significant interaction with N, K and Mg. The positive interaction of P with macronutrients may be associated with improvement in growth and yield of crop plants with the P fertilization. Increased growth and yield required more nutrients compared to low growth and yield. Wilkinson *et al*. [91] also reported that increased growth requires more nutrients to maintain tissue composition within acceptable limits; mutually synergistic effects for N and P promote growth even more. Most P–lime interactions are intimately associated with toxic soil Al that limits root growth and proliferation and nutrient uptake [93]. Among micronutrients, P-Zn interaction is widely reported in the literature [91, 93]. In Brazilian Oxisols, the repose of upland rice to P application is very common and this generally induces Zn deficiency [94]. The Zn deficiency in this situation is associated with the rapid growth of plants and soil-available Zn cannot fulfill the demands of rapidly growing plants. Zinc deficiency-induced P toxicity, a phenomenon that has been well described [95].

K interaction with other nutrients is an important aspect of improving crop yields. K plays several roles in plant metabolism and to perform these roles positively, it should interact positively with other essential nutrients. Positive interactions of K with N and P have been reported [96]. Dibb and Welch [97] reported that the increased K allowed for rapid assimilation of absorbed NH_4^+ ions in the plant, maintaining a low, nontoxic level of NH_3. Increased yield of crops with the addition of N and P requires a higher level of K in the soil [96, 98]. Antagonistic interaction between K^+ and Mg^{2+} and Ca^{2+} uptake has been reported [76, 96]. Fageria [96] reported that reduction in Ca uptake with increasing K concentration in the growth medium is closely associated with increased uptake of K, indicating that there may have been a competitive effect. A competition between K and Ca^{2+} and Mg^{2+} due to the physiological properties of these ions has been reported [76]. K and micronutrient interactions have been observed with many crop plants. Gupta [99] reported that high K rates reduced B uptake and intensified B deficiency in crop plants. Dibb and Thompson [96] reviewed the interaction between K^+ and Cu in crop plants and reported that Cu^{2+} uptake increased with the addition of K^+. Matocha and Thomas [100] reported that Fe application with K^+ increased sorghum yield. Fageria [101] reported that Fe^{2+} toxicity in flooded rice reduced with the addition of an adequate rate of K^+ in the soil. These authors also reported that plants with adequate K^+ have more metabolic activity in the roots and high levels of Fe^{2+} excluding power. Dibb and Thompson [96] in a review reported that K^+ improved Mn^{2+} uptake when this element is in low concentration in the growth medium and decreased its uptake when it is present in a higher concentration that might be toxic. The beneficial effect of K on the uptake of Zn^{2+} has been reported [96].

Many factors affect Ca uptake and activity. Extensive interactions of other mineral elements with Ca have been reported [102, 103]. The ions that strongly inhibit Ca uptake are H^+, K^+, Na^+, Mg^{2+}, Al^{3+} and NH_4^+. The inhibitory role of NH_4^+ on Ca uptake is of special interest since NH_4^+ fertilization of plants is a common practice. Nutrient solutions containing some $NH4^+$ become low in pH (near 4.0 or below) when sorghum and corn are grown in them [104]. The uptake of cations at low pH (high H^+ concentration) is less than that at higher pH value and Ca uptake is depressed more than uptake of the other cations [49]. Ammonium is absorbed more readily than is Ca and this can inhibit growth. Growth inhibition of sorghum by NH_4^+ was closely related to decreases in nutrient solution pH imposed by NH_4^+ uptake. Growth inhibition by NH_4^+ may be a result of Ca deficiencies that occur under these conditions.

Nutrient interactions at the root-soil interface are an important aspect of the mineral nutrition of plants. Knowledge of the interfacial processes may lead to a better understanding of the relationship between crop yield and the nutrient level of soils. There is no easily recognizable nutrient balance within the plant for best crop production, except when an essential nutrient becomes so low as to limit growth [105]. Ohno and Grunes [106] reported that K^+ depresses the shoot concentration of Mg^{2+} by reducing the translocation of Mg from the root to the shoot of wheat plants. Wilkinson [107] reported that high levels of soil K^+ depressed Mg^{2+} uptake by plants. Similarly, Ologunde and Sorensen [108] using a sand culture system, grew sorghum with various levels of K and Mg^{2+}. They found that K^+ depressed the concentration of Mg^{2+} substantially in the shoots, but the effect of Mg^{2+} on K^+ is a slightly antagonistic effect or no effect at all. Hannaway *et al*. [109] using solution culture, found that increasing levels of K^+ in solution decreased the shoot concentration of Mg^{2+} in tall fescue. Huang *et al*. [110] also reported that net Mg^{2+} translocation from roots to shoots is depressed by increasing root K^+ concentration. Spear *et al*. [111] who studied a nutrient solution culture and Christenson *et al*. [112] who worked in soils, reported interactions between K^+, Ca^{2+} and Mg^{2+} absorption by whole plants. These studies showed that K^+ and Ca^{2+} suppressed Mg^{2+} content in plant tissue, but the effect depended on the concentration of the ions and soil properties. Moore *et al*. [113] and Maas and Ogata [114] studied the influence of pH and Mg and Ca^{2+} concentrations in solutions on Mg^{2+} uptake by excised barley and corn roots, respectively. In both reports, it was concluded that enhanced solution Ca^{2+} concentrations reduced Mg^{2+} uptake rate by suppressing the Mg^{2+} transport capacity of the root rather than competing with Mg^{2+} for absorption sites. Al tolerance has been associated with greater uptake of Mg^{2+} in potato and corn cultivars [115]. Similarly, Al^{3+} toxicity in wheat is prevented by increasing the concentrations of Mg^{2+}, Ca^{2+} and K^+ in nutrition solution, either individually or collectively [116]. The beneficial effects of these elements are probably due to a competitive reduction in Al–root contact or to a decrease in Al^{3+} activity rather than to the nutrient supply [115].

S interaction with N is very common and the S requirements of crops are enhanced with the increase of N in the growth medium. The main reason for the interaction of S with N may be a significant increase in the growth of plants with N addition, which may cause dilution of S in plants [91]. Robert and Koehler [117] reported that insufficient S, especially when large amounts of N were applied, resulting in a decreased grain yield and a diminished S amino acid content of the grain protein. Soliman *et al*. [118] reported that in calcareous soils, S reduces pH and improves uptake of micronutrients like Fe, Mn and Zn. Uptake of P may also improve in calcareous soils with the application of S due to the reduction of pH. It has been reported in Japan that Zn deficiency of lowland rice may be induced by excess amounts of sulfides in soils [119]. Similarly, Suzuki [85] reported that excess Zn induced S deficiency in rice plants. Rehm and Caldwell [120] found that sulfate uptake was higher when N was added as ammonium nitrogen, but sulfate uptake in the presence of nitrate was similar to that where no N was added. S application was reported to decrease molybdenum (Mo) content in pea plants in low-Mo soils and pea plants showed Mo deficiency [121]. This may be attributed primarily to competition in the absorption site of plant roots between molybdate and sulfate ions, which are similar in size and charge and, besides, to the physiological inhibition of Mo utilization by sulfates within the plant body [85]. Since Mo affects the biological N fixation, the interaction between S and Mo has special significance for legume crops. Tanaka *et al*. [122] reported that the application of gypsum to lowland rice reduced soil pH and induced iron toxicity.

Management Practices to Improve Nutrient Use Efficiency: Management of nutrients is an important aspect of improving crop productivity. Nutrient management in crop production means supplying essential plant nutrients to a crop in adequate amount and form to get maximum economic yield in a given agro-ecological region. The nutrient requirements of a crop vary according to the soil, climatic conditions, cultivar planted and management practices adopted by a farmer. Thus, nutrient management strategies should vary according to the type of soil, climatic conditions, crop species, cultivar within species and socioeconomic considerations. Soil acidity is one of the most important constraints in crop production in many regions of the world. Generally, soil acidity is measured in terms of H^+ and Al^{3+} ions in the soil solution. However, acid soil toxicity is not caused by a single factor but a complex of factors including toxicities of Al^{3+} and H^+ and deficiencies of many macro-and micronutrients [123, 124]. Liming is an effective and widespread practice for improving crop production on acid soils [123]. Liming acid soils improves soil physical, chemical and biological activities and consequently improves crop yield and N use efficiency [15, 123]. Soil acidity indices like pH, base saturation and Al saturation are used as bases for liming acid soils. Furthermore, economic considerations are also important criteria in determining the quantity of lime applied to acid soils. Activities of most of the beneficial microorganisms that are involved in the process of mineralization of N and biological N fixation are inhibited under acidic conditions.

Liming acid soil influences physical, chemical and biological properties in favor of higher crop yields and consequently higher P use efficiency. Liming supplies Ca^{2+} and Mg^{2+} and neutralizes Al^{3+} and H^+ ion toxicity. Soil pH is improved by liming, which produces many beneficial effects for plant growth and nutrient uptake. In variable-charge soils, a decrease in pH increases the anion exchange capacity, increasing the retention of P [125]. Hence, improving crop yields on these soils require high P rates [94]. The P increase in the pH range of 5 to 6.5 is associated with the release of P ions from Al and Fe oxides, which are responsible for P fixation. At higher pH (>6.5) the reduction of extractable P is associated with fixation by Ca ions. The liming of acid soils results in the release of P for plant uptake [126]. Bolan *et al*. [126] reported that in soils high in exchangeable and soluble Al, liming might increase plant P uptake by decreasing Al, rather than by increasing P availability per se. This may be due to improved root growth where Al toxicity is alleviated, allowing a greater volume of soil to be explored [127].

Liming acid soils not only decreases soil Al but also can increase retention of applied K^+ and thereby decrease K^+ leaching. Liming increases K^+ retention in soils by replacing Al^{3+} on the exchange sites with Ca^{2+}, allowing K^+ to compete better for exchange sites and increasing the effective cation exchange capacity. Improvements in these chemical properties improve crop yield and lead to higher K use efficiency [87]. Fageria [94] also reported that improvements in these properties increase the grain yield of many crops in acid soils. Improvements in soil pH with liming increases shoot dry weight, grain yield and many panicles in upland rice. An increase in yields means an improvement in K^+ use efficiency in crop plants. Liming can also improve root development in the limed soil depth by neutralizing Al^{3+} and improving pH and Ca^{2+} and Mg^{2+} contents, which can improve uptake of water and nutrients. Muzilli [128] studied the response of soybean to levels of K fertilization in the presence and absence of lime in a Brazilian Oxisol. Soybean yield response to K was higher in limed plots compared to unlimed plots. Leaf analysis for K also showed a significant increase in K content in the limed plots compared to unlimed plots. Fageria and Baligar [123] suggested that elimination of toxic quantities of Al^{3+} and Mn^{2+} and addition of adequate quantities of Ca^{2+} and Mg^{2+} are the goals of liming, especially in highly leached and weathered soils.

It is common practice to lime several weeks before planting to allow sufficient time for the lime to react with the soil. This may greatly alter the S-supplying capacity of soils, for the rise in soil pH decreases the SO_4^{2-} adsorption capacity of the soil [129]. This effect is usually attributed to a competition between OH^- and SO_4^{2-} for adsorption sites on Al^{3+} and Fe^{3+} hydroxides [130]; by making phosphate compounds more soluble at higher pH, there may be more phosphate ions to compete for the sites as well [131]. Glass [3] reported that for the divalent anions like SO_4^{2-}, adsorption on soil colloids is a function of pH. Above pH 6.0 to 6.5, there is only very slight adsorption. In acid soils, however, particularly those high in Fe^{3+} and Al^{3+} oxides, adsorption may be substantial. Similarly, Bolan *et al*. [126] and Marsh *et al*. [132] reported that, as a general rule, many soils absorb little, if any, SO_4^{2-} once pH exceeds about 6.0. Liming may also increase the rate of organic S mineralization by creating a more favorable environment for microbial activity [133]. By increasing the mineralization of organic S into SO_4^{2-} and decreasing SO_4^{2-} adsorption, liming could accelerate the movement of SO_4^{2-} through the profile. In acid soils, this may result in decreased uptake of S by the plant, particularly if root development in the subsoil is inhibited, such as by high exchangeable Al^{3+}. Thus, rather than increasing the S availability, as observed under un-leached conditions, liming soil and subsequent leaching may decrease the S supplying capacity, particularly over a long period [129]. After liming an acid soil, Elkins and Ensminger [134] observed an increase in the SO_4^{2-} concentration in the soil solution and S uptake by soybean was improved. However, Bolan *et al*. [135] reported that in the absence of active uptake by plants, any SO_4^{2-} released into soil solution by liming is susceptible to leaching and may be lost to subsoil horizons.

The use of adequate N rates is essential for the efficient use of N fertilizer and to maintain the economic sustainability of cropping systems. Excessive use of N fertilizers is economically unfavorable, because incremental increases in yield diminish with increasing amounts of N applied and it could lead to detrimental effects on the quality of soil and water resources [15]. Nitrogen application timing is also important for improving crop yields and N use efficiency. The use of proper source, method and P rate is an important management practice to improve P use efficiency in crop plants. There are several chemical fertilizer sources of P. Among these sources, water-soluble sources are more effective for annual crops. Water-insoluble or citric acid-soluble sources of P are effective for acid soils. P should be applied at the time of sowing of annual crops in bands in low-P soils. This reduces the fixation of the fertilizer P to a minimum as it allows the crop the best opportunity to compete with the soil P utilization [24]. The band P usually increased early crop growth more than the broadcast placement because of increased uptake [28, 136]. The timing of fertilizer K^+ application is an important management tool in this effort. Maximum efficiency is obtained when K^+ is applied so that it is available for uptake by the plants as needed. Generally, K^+ fertilizer is applied as a basal application at the time of sowing because of its relative immobility in clay soils. Generally, fertilizers are applied as broadcast, in a furrow, or a band below, or alongside the planted seed row. As a relatively immobile ion in soil, K^+ supply to roots depends mostly on diffusion [28]. This means that in K^+-deficient soil, band application of K^+ may be more efficient than a broadcast application because the mean level of K^+ within developing roots and diffusion rates are increased.

Application of the optimum rate is essential for improving Ca^{2+} use efficiency by crop plants. This rate may vary with crop species, cultivar within species and soil type and climatic conditions. All these factors should be taken into account when defining the optimum rate of Ca^{2+} for a given crop. Soluble Mg^{2+} sources are more effective in supplying Mg^{2+} to crop plants compared with low-soluble Mg^{2+} sources [31]. The best method to determine the appropriate Mg rate is the relationship between the exchangeable Mg^{2+} content of the soil and

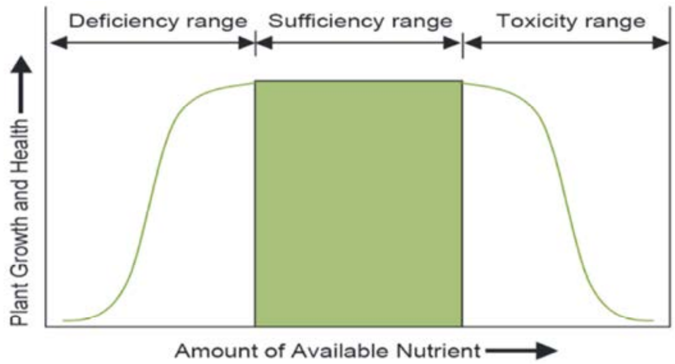

Fig. 1: Relationship between plant growth and health and amount of nutrient available

grain yield. Top-dressing of ammonium sulfate can furnish N as well as S requirements of crops and avoid much leaching. The use of an adequate rate of S is an important strategy to improve crop yields and maximize S use efficiency by crop plants. As far as methods of S application are concerned, S can be applied in the band as well as broadcast. The use of the appropriate method, source and rate are important management practices to improve micronutrient use efficiency by crop plants. Besides, the soil test can be an important criterion for micronutrient fertilizer recommendations. Furthermore, the use of micronutrient efficient crop species or genotypes within species is another important practice to reduce the cost of crop production and environmental pollution. Availability of essential micronutrients decreased with increasing pH, except Mo. Since Mo becomes more available with increasing pH, liming will correct a deficiency in acid soils, if the soil contains enough of the nutrient.

Diagnosing Nutrient Toxicities: Plants require essential nutrients for normal functioning and growth. A plant's sufficiency range is the range of nutrient amount necessary to meet the plant's nutritional needs and maximize growth (Figure 1). The width of this range depends on individual plant species and the particular nutrient. Nutrient levels outside of a plant's sufficiency range cause overall crop growth and health to decline due to either a deficiency or toxicity. Nutrient deficiency occurs when an essential nutrient is not available in sufficient quantity to meet the requirements of a growing plant. Toxicity occurs when a nutrient is more than plant needs and decreases plant growth or quality. Nutrient toxicity is less common than deficiency symptoms and most likely occurs as a result of over-application of fertilizer or manure. As insufficient nutrient content can cause visual symptoms to occur in plants, so too can an excess. Plants with excess N turn a deep green color and have delayed maturity. Due to N's positive effect on vegetative growth, excess N results weak stems, possibly causing lodging [137]. New growth will be succulent and plant transpiration high/low water use efficiency. N toxicity is most evident under dry conditions and may cause a burning effect. Plants fertilized with ammonium (NH_4^+)-based fertilizers may exhibit NH_4^+ toxicity, indicated by reduced plant growth, lesions occurring on stems and roots and leaf margins rolling downward, especially under dry conditions. Excess P indirectly affects plant growth by reducing Fe, Mn and Zn uptake; thus, potentially causing deficiency symptoms of these nutrients to occur. Zn deficiency is most common under excess P conditions. Due to a cation imbalance, K toxicity can cause reduced uptake and subsequent deficiencies of Mg and in some cases, Ca.

For many crops, the range between deficiency and toxicity is narrower for micronutrients than macronutrients. This is particularly true for B in which the average sufficiency and toxicity ranges for various crops overlap one another: 10-200 ppm (sufficiency range) and 50-200 ppm (toxicity range; [138]). B toxicity results in chlorosis followed by necrosis. Symptoms begin at the leaf tip and margins and spread toward the midrib. As the toxicity progresses, older leaves will appear scorched and fall prematurely. In sugar beet, a yellow-tinted band will occur around leaf margins [105]. Other micronutrients causing potential toxicity symptoms include Cu, Mn, Mo, Ni and Zn. Studies suggest excess Cu will displace Fe and other metals from important areas in the plant, causing chlorosis and other Fe deficiency symptoms, such as stunted growth, to appear [24]. High Ni concentrations can also cause Fe to be displaced. Interveinal chlorosis may appear in new leaves of Ni toxic plants and growth may be stunted. Mn toxicity symptoms are generally characterized by blackish-brown or red spots on older leaves and an uneven distribution of chlorophyll, causing chlorosis and necrotic lesions on leaves. While Mo toxicity does not pose serious crop problems (crops may appear stunted with yellow-brown leaf discolorations), excess amounts of Mo in forage are toxic to livestock [139]. Zn toxicity is not common but can occur on very saline soils. Symptoms include leaves turning dark green, chlorosis, interveinal chlorosis and a reduction in root growth and leaf expansion. Excess Zn may induce Fe deficiency.

CONCLUSION

Plants require elemental nutrients in various amounts although the amounts vary greatly with species, genotype, soil and environmental factors. Essential elements are generally defined as either a macronutrient or micronutrient based on the relative amount required by the plant. The processes and rates of natural accumulation of nutrients in the soil (mineralization, organic matter decomposition, etc.) are complex and highly dependent on soil type and local conditions. For grain crops, as the seed is produced and removed from the field, nutrients are lost every season. This loss must be replaced naturally or with fertilizers to maintain production. In most cases, the removal of at least some nutrients is faster than replenishment by natural processes. In such situations, nutrient reserves are exhausted and soils become deficient. The higher-yielding environment has the greater the demand for all nutrients. This can be especially important for the macronutrients N, P and K as they are needed in the greatest amounts. However, yields can be limited or even severely restricted via deficiencies in any of the other nutrients. However, when the nutrient concentration drops below a certain optimal level, plant growth and/or development can be negatively impacted. Nutrient deficiencies and toxicities cause crop health and productivity to decrease and may result in the appearance of unusual visual symptoms. Understanding each essential nutrient's role and mobility in the plant can help determine which nutrient is responsible for a deficiency or toxicity symptom. Deficiencies of mobile nutrients first appear in older, lower leaves, whereas deficiencies of immobile nutrients will occur in younger, upper leaves. Nutrient toxicity is most often the result of over-application, with symptoms of abnormal growth (excessive or stunted) chlorosis, leaf discoloration and necrotic spotting. When in excess, many nutrients will inhibit the uptake of other nutrients, thus potentially causing deficiency symptoms to occur as well. As a diagnostic tool, visual observation can be limited by various factors, including hidden hunger and pseudo deficiencies and soil or plant testing will be required to verify nutrient stress. However, the evaluation of visual symptoms in the field is an inexpensive and quick method for detecting potential nutrient deficiencies or toxicities in crops and learning to identify symptoms and their causes is an important skill for managing and correcting soil fertility and crop production problems.

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