Nutrient Management Strategies Based on Microbial Functions

10

C.M. Mehta, Byiringiro Emmanuel,
Amit Kesarwani, Kanak Sirari, and Anil K. Sharma

Abstract

There is a common misconception that nutrient deficiency can only be managed by the application of required fertilizers into the field, but most of the times even after applying fertilizers, plants are not able to attain proper growth. The major cause is unavailability or inadequate availability of nutrients to the plants. Therefore, there is a need to understand different nutrient management practices of the field. Millions of microbes are present in the soil, but still only a fraction of this microbial population is known to researchers. Therefore, the specific role of these microbes present in the soil cannot be denied. So far, researchers identified few microbial populations that are characterized for their significant role in nutrient management of the soil, but the information about the characterization and mechanism of these beneficial microbes has not been documented. In this chapter, an attempt has been made to explain the plant-required nutrients, their deficiency, and the role of different beneficial microbes that can manage the nutrient requirement of plants.

Keywords

Microbes • Functions • Nutrient • Management • Micronutrients • Macronutrients

10.1 Introduction

Plant nutrients, which are readily available in soil, play an important role in crop growth and productivity. Availability of nutrients to the plants depends on their presence or abundance in the soil. The external source for enriching soil nutrients is mainly chemical and biological fertilizers

---

C.M. Mehta (✉) • B. Emmanuel • A. Kesarwani
K. Sirari
School of Agriculture, Lovely Professional University, Jalandhar-Delhi G.T. Road, NH1, Phagwara, Punjab 144411, India
e-mail: chandra_m_mehta@yahoo.com

A.K. Sharma
Department of Biological Sciences, GBPUA&T
Pantnagar, U.S. Nagar, Uttarakhand 263145, India

D.P. Singh et al. (eds.), *Microbial Inoculants in Sustainable Agricultural Productivity*,
DOI 10.1007/978-81-322-2644-4_10

such as urea, diammonium phosphate (DAP), superphosphate, composts, and biofertilizers. The most important factors that affect the availability of these nutrients to the plants are timing of fertilizer application and their proper quantity. Sometimes, just after the harvesting of the first crop, without knowing the requirement of nutrient to the soil, the farmer applies additional fertilizer into the soil. This increased amount of nutrient into the soil is not always beneficial to the plant. At times, it shows adverse effects on the crop, such as higher concentration of nitrogen, which can increase the plant growth but somehow reduce the availability of other nutrients to the plant; similarly, overapplication of phosphorus (P) can result in P runoff causing eutrophication of surface water (Barlog and Grzebisz 2004). Therefore, nutrient management of the soil is required. Most of the nutrient management practices are controlled by human activities, but microbes that are present in the soil also play an important role in nutrient management.

In a given set of environmental conditions, the unpredictable nature and biosynthetic capabilities of microbes have made them important candidates for resolving nutrient-related issues in rhizosphere (the area around the roots). Soil microbes can transform organic molecules into mineral elements that are readily available to plants and they also help to maintain soil structure by producing cementing compounds. Most of the bacterial communities have a mucilaginous sheath that helps to bind small soil aggregates; similarly, fungal communities have a hyphal structure that spread all over the soil and, because of this, small soil particles are trapped in between these hyphal structure that helps to hold soil aggregates. During decomposition, soil microbes (mainly mesophilic and thermophilic) convert raw organic material into humus (Mehta et al. 2014). This conversion starts with the breakdown of complex molecules into simpler molecules. These simpler molecules, in the form of essential minerals, are released into the soil and help plants growing in nearby areas (Fig. 10.1). In addition to increased nutrient availability, these microbes also help in reducing the disease and nutrient loss, as well as help in degrading toxic elements

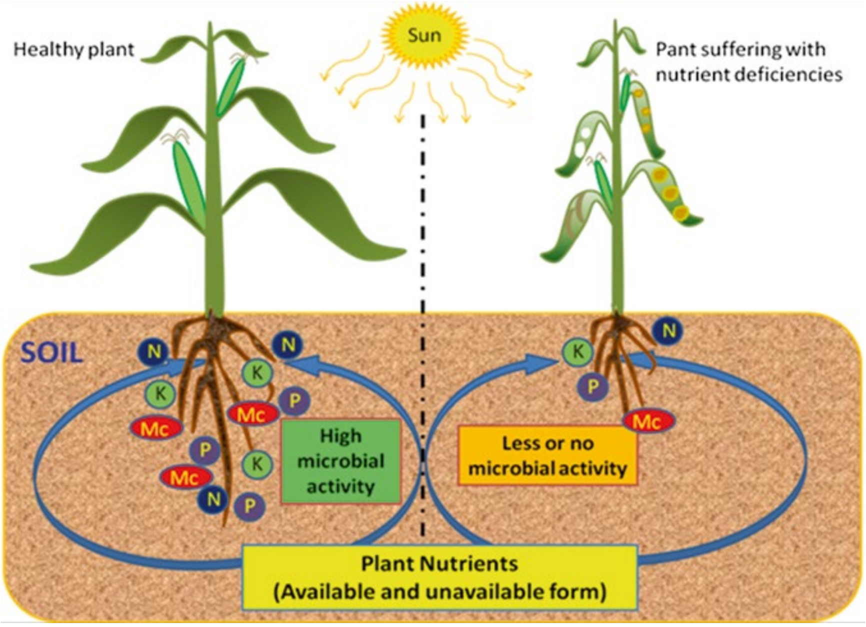

Fig. 10.1 Potential role of soil microbes in nutrient management (*K* potassium, *P* phosphorus, *N* nitrogen, *Mc* other nutrients)

present in the soil. Plant health totally depends on the microbial community present in the rhizospheric soil. In healthy rhizosphere, beneficial microbes work as a mediator between plant life and soil life that helps produce healthy crops, whereas, in unhealthy rhizosphere, the soil is dominated by different soil-borne plant pathogens that can attack on the crops and restrict their physiological as well as morphological activities. Therefore, there is a greater need for better understanding of microbe-mediated nutrient management practices.

10.2 Role of Nutrient in Plant Health

Since centuries it is known that plants obtain nourishment from the soil. During the first half of the nineteenth century, it was found that plants require certain nutrients known as essential nutrients and that nutrients are taken up by the roots in the form of inorganic ions. Nutrients are indispensable as plant constituents, for biochemical reactions, and for the production of organic materials referred to as photosynthates (carbohydrates, proteins, fats, vitamins, etc.) by photosynthesis. In crop production, adequate mineral nutrition is important to produce healthy crops with high and good quality. The balanced plant nutrient is a pivotal factor, which helps crops to give the desired yield potential. Plants can get their required nutrients from fertilizers, organic manures, the atmosphere, etc.

Balanced nutrients are necessary for plant structures and for all physiological processes; for example, nitrogen and magnesium are a fundamental part of the chlorophyll required in photosynthesis process. On the other hand, phosphorus stimulates energy production and its storage. In addition, nitrogen is necessary for nucleic acid synthesis, and potassium is required for osmotic maintenance and enzyme activation (Waraich et al. 2011). Currently, there are 17 essential plant nutrients. Some of them (carbon and oxygen) are taken by the plant from air, others including water can be taken up from the soil. To produce a healthy plant, the following mineral nutrients should be supplied to growing media (Allen and Pilbeam 2007):

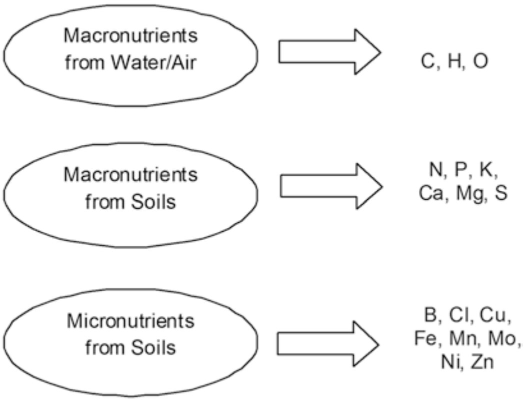

Fig. 10.2 Essential plant nutrients required for plant growth

Essential plant nutrients include *macronutrients and micronutrients.* In *macronutrients*, nitrogen (N), phosphorus (P), and potassium (K) are *primary nutrients*. Those nutrients are usually less in soil because plants use them in large quantity and therefore they supply to the soil at higher rates compared to secondary nutrients and micronutrients. Another group of s*econdary nutrients* includes calcium (Ca), magnesium (Mg), and sulphur (S), and they are supplied in smaller amounts compared to primary nutrients. *Micronutrients* include iron (Fe), chlorine (Cl), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), and nickel (Ni): they are required even in smaller amounts compared to secondary nutrients (Fig. 10.2).

10.2.1 Essential Plant Nutrients

A total of 17 elements are essential for the growth and full development of higher green plants according to the criteria laid down by Arnon and Stout (1939). These criteria are as follows:

1. The element must be essential for supporting normal growth and reproduction, and the plant cannot complete its life cycle or set the seeds if the element is absent.

2. The element is specific and its function must not be replaced by another.
3. The element must be directly implied in plant metabolism.

The basis of most plant micronutrients was initiated from 1922 to 1954. In 1987, Brown et al. established the essentiality of nickel (Ni), though there is no agreement whether Ni is essential or beneficial nutrient. However, this list may not be considered as final and it is probable that more elements may prove to be essential in future. The chronology discoveries, form absorbed, and the concentration in plant dry matter of nutrient essentiality are summarized in Table 10.1.

Essential nutrients can also be categorized into four broad categories depending on their functions. These categories are as follows:

1. Essential nutrients that are biomolecules and enhance cell structure (e.g. carbon, oxygen, hydrogen, and nitrogen).
2. Essential nutrients that are chemical energy-related compounds in plants (e.g. magnesium in chlorophyll and phosphorus in adenosine triphosphate (ATP)).
3. Essential nutrients that activate or inhibit enzymes.
4. Essential nutrients can change the movement of water molecules within a cell.

10.2.1.1 Macronutrients

Macronutrients required in plants can be categorized into two groups: primary nutrients and secondary nutrients.

10.2.1.1.1 Primary Nutrients

The primary nutrients are nitrogen, phosphorus, and potassium. For most crops, these three mineral nutrients are needed in large amounts than other nutrients.

(a) Role of Nitrogen

Nitrogen is one of the three nutrients most important for plant growth and it is required in large quantity. It stimulates fast vegetative growth, enhances the maturity of the crops, and boosts the development of seeds. It is essential for most metabolic processes that take place in the plant as a constituent of amino acids that are necessary for proteins and other product synthesis. Nitrogen

Table 10.1 Essential plant nutrients, forms taken up, and their typical concentration in plants (Roy et al. 2006)

Nutrient (symbol)	Essentiality established by	Forms absorbed	Typical concentration in plant dry matter
Macronutrients			
Nitrogen (N)	de Saussure	NH^{4+}, NO3	1.5 %
Phosphorus (P, P_2O_5)	Sprengel	H_2PO^{4-}, HPO_4^{2-}	0.1–0.4 %
Potassium (K,K_2O)	Sprengel	K^+	1–5 %
Sulphur (S)	Salm-Horstmann	SO_4^{2-}	0.1–0.4 %
Calcium (Ca)	Prengel	Ca^{2+}	0.2–1.0 %
Magnesium (Mg)	Sprengel	Mg^{2+}	0.1–0.4 %
Micronutrients			
Boron (B)	Warington	H_3BO_3, $H_2BO_3^-$	6–60 µg/g (ppm)
Iron (Fe)	Gris	Fe^{2+}	50–250 µg/g (ppm)
Manganese (Mn)	McHargue	Mn^{2+}	20–500 µg/g (ppm)
Copper (Cu)	Sommer, Lipman	Cu^+, Cu^{2+}	5–20 µg/g (ppm)
Zinc (Zn)	Sommer, Lipman	Zn^{2+}	21–150 µg/g (ppm)
Molybdenum (Mo)	Arnon and Stout	MoO_4^{2-}	Below 1 µg/g (ppm)
Chlorine (Cl)	Broyer and others	Cl^-	0.2–2 %
Nickel (Ni)	Brown and others	Ni^{2+}	–

is considered as a fundamental component of the green pigment known as chlorophyll, necessary in photosynthesis process. Photosynthesis may be defined as a process by which green plants utilize sunlight to synthesize their own nutrients (carbohydrates) from atmospheric carbon and water in the presence of the green pigment known as chlorophyll. The required energy for growth and development is taken from the synthesized carbohydrates (sugars). Here is a summary of the chemical equation of this complex process:

$$6CO_2 + 12H_2O + 672\,\text{Kcal light energy} \rightarrow C_6H_{12}O_6 + 6H_2O + 6CO_2$$

Nitrogen plays an essential role in temperature stabilization. High temperature is proportional to the light intensity and it can have negative effects on mineral nutrient uptake and plant growth. Among mineral nutrients, it has an important role in sun radiation use and metabolism of carbon during photosynthesis process (Kato et al. 2003; Huang et al. 2004).

(b) Role of Phosphorus

Phosphorus is an essential element considered as fundamental blocks of life, the ribonucleic acid (RNA), deoxyribonucleic acid (DNA), phospholipids, coenzymes, nicotinamide adenine dinucleotide phosphate (NADP), and most importantly ATP; it is also needed for various biochemical and physiological processes such as transfer of energy, protein synthesis, and other functions (Prabhu et al. 2007).

(c) Role of Potassium

Plant nutrients play a critical role and enhance plant resistance (Marschner 1995). Potassium (K) is required for the protection of crop plants from unfavourable situations. Also, it is necessary for photosynthesis, translocation of photosynthesis products from source organs to sink organs, turgidity keeping and activation of enzymes to metabolize carbohydrates for the manufacture of amino acids and proteins, under stress conditions, hasten cell multiplication and growth by stimulating the transfer of starches and sugars between cell components, improve stalks and stem rigidity, and increase disease resistance as well as drought tolerance and control of osmotic potential (e.g. opening and closing of stomata); it is also responsible for firmness, texture, size, and colour of fruit crops, and is essential for oil content of oil crops (Marschner 1995; Mengel and Kirkby 2001).

10.2.1.1.2 Secondary Nutrients

The secondary nutrients are calcium, magnesium and sulphur. For most crops, these three are needed in lesser amounts than the primary nutrients.

(a) Role of Calcium

Various plant physiological processes are moderated by calcium and its action occurs basically at tissue, cellular, and molecular levels that can affect growth and plant responses to environmental stresses in plant. Calcium is immobile and persists in the older tissue of the plant. It has the ability to neutralize organic acids produced during the growth process and to participate in carbohydrate transport and absorption of nitrogen (Waraich et al. 2011). Calcium supply induces stomatal closure, when temperature is low, and it stimulates the elasticity and expansion of cell walls, which in turn prevent plant-growing regions to become rigid and brittle. It has also been shown that Ca^{2+} mediates *abscisic acid* (ABA) that controls stomatal closure and releases in internal guard cell stores or the apoplast

(Wilkinson et al. 2001). Calcium plays an important role in regulating cold temperature stresses and recovery from injury, and it allows good performance of plants during cold stress periods (Palta 2000). Calcium plays a very prominent role in the maintenance of cell structure and is involved in the production of new growing points and root tips. It is responsible for the plasma membrane enzyme activation such as ATPase that is required for the pump-back of nutrients lost during cell membrane damage and helps the plant recover from cold injury. It also acts as calmodulin that regulates plant metabolism and expedites plant growth under cold environment. In addition, it is considered as a fundamental brick in the plant because it is necessary for the manufacture and development of a cell (Waraich et al. 2011).

(b) Role of Magnesium

Magnesium (Mg) participates in different physiological and biochemical processes that can influence plant growth and its development (Waraich et al. 2011). It is important for photosynthesis process and many other metabolic processes. Small fluctuation in magnesium levels can strongly affect the main chlorophyll enzymes (Shaul 2002). Many findings confirmed that Mg plays an essential role in electron transport chain of chloroplast. Mg transfers energy from photosystem II to NADP$^+$ and protects thylakoid membrane by reducing accumulation excitation energy and oxidative damage (Halliwell 1987). It has been reported that, magnesium promots antioxidative enzymes and antioxidant molecule concentration in bean (Cakmak and Marschner 1992; Cakmak 1994), *Mentha pulegium* (Candan and Tarhan 2003), maize (Tewari et al. 2004), pepper (Anza et al. 2005), and mulberry (Tewari et al. 2006). Magnesium plays a major role in water and nutrient uptake by increasing the root growth and root surface area. As a chlorophyll component, Mg enhances sucrose production and its translocation for further use (Waraich et al. 2011). It stimulates the transfer of carbohydrates across phloem and reduces the production of reactive oxygen species (ROS). Under high- or low-temperature stress, Mg protects chloroplast from photooxidative damage. Chloroplast structure maintenance by Mg nutrition stimulates photosynthesis activities under extreme temperature, thereby increasing plant productivity (Waraich et al. 2011).

(c) Role of Sulphur

Sulphur plays an important role in amino acid synthesis that results in protein production. It is also needed in chlorophyll production and uses phosphorus as well as other essential nutrients. It is considered as nitrogen for crop yield and quality giving. Sulphur enhances the quality of crop grains and improves nitrogen use efficiency during protein synthesis in crops that require a high amount of nitrogen. It is also important for yield and protein quality of forage and grain crops as well as quality of fibre crops (Reddy 2012).

10.2.1.2 Micronutrients

Out of 17 essential plant nutrients, eight are micronutrients because plants need them in relatively small amounts. They include chlorine (Cl), manganese (Mn), boron (B), copper (Cu), iron (Fe), molybdenum (Mo), zinc (Zn), and nickel (Ni). Their roles in plant health are narrated subsequently.

(a) Role of Chlorine

Chlorine is essential in photosynthesis, where it is involved in the evolution of oxygen. It increases cell osmotic pressure and the water content of plant tissues. It is found in many bacteria and fungi, and it reduces the severity of certain fungal diseases (Reddy 2002).

(b) Role of Manganese

Manganese is an essential nutrient involved in photosynthesis and nitrogen metabolism, as well as to form other compounds required for plant metabolism. Manganese is essential for regulation of adverse temperature conditions by promoting photosynthesis activity and metabolism of nitrogen within the plant body. Manganese is necessary to prevent chlorosis between veins and necrotic brown spots on old leaves, and it decreases the shedding of premature leaves. It is known as an enzyme activator in plant body, mostly in oxidation–reduction, decarboxylation, and hydrolytic reactions, and hence intervenes in ROS detoxification (Marschner 1995). Recent findings confirm that manganese has the ability to inhibit the production of oxygen-free radicals and enhances antioxidative compounds and enzymatic activities under temperature stress (Aktas et al. 2005; Turhan et al. 2006; Aloni et al. 2008).

(c) Role of Boron

Boron can intervene in various physiological and biochemical processes during plant growth and development such as cell elongation, cell multiplication, cell wall biosynthesis, membrane function, nitrogen metabolism, photosynthesis, and uracil synthesis (Marschner 1995). It can promote the antioxidant activities of the plant and prevent the damage that can be induced by temperature stress. Boron supply can improve the transport of sugars within the plant and results in seed germination and grain formation (Waraich et al. 2011). Boron application enhances carbohydrates and reduces phenolic compounds in leaves. This stimulates photosynthetic rate by inhibiting the production of ROS species (Waraich et al. 2011).

(d) Role of Copper

Copper (Cu) is an essential redox-active transition metal and it is involved in many physiological processes in plants such as chlorophyll formation, although its specific role is still unclear. Under physiological conditions, Cu exists as Cu^{2+} and Cu^{+}. Cu acts as a structural element in regulatory proteins and participates in photosynthetic electron transport, mitochondrial respiration, oxidative stress responses, cell wall metabolism, and hormone signalling; it is also thought to be involved in protein synthesis. It intensifies colour, improves the flavour of fruits and vegetables, increases sugar content, and plays a major role in reproductive stages (Marschner 1995; Raven et al. 1999).

(e) Role of Iron

Iron is more abundant, though its quantity is low and not available for plant and microorganism needs, due to the low solubility of its mineral that contains iron, particularly in arid zones with alkaline soils. Iron is an essential nutrient in crops, for enzymes such as cytochrome that is required in electron transfer chain. It synthesizes chlorophyll and maintains the chloroplast structure and enzyme activity (Mamatha 2007; Ziaeian and Malakouti 2001; Zaharieva and Abadia 2003; Welch 2002). In addition, iron is necessary for chlorophyll production. For instance, iron is a site activator of glutamyl-tRNA reductase, an enzyme necessary for 5-aminolevulinic acid, which is a progenitor of chlorophyll (Kumar and Soll 2000).

(f) Role of Molybdenum

Molybdenum (Mo) is needed in biological nitrogen fixation (nodulation) by legumes and it is involved in protein synthesis by reducing nitrates. For normal growth, the plant requires 0.1–2.5 ppm in its tissues. The recommended dose for Mo soil application ranges from 0.1 to 0.5 Ib Mo/acre (Reddy 2012).

(g) Role of Zinc

Zinc has a crucial role in plant enzymes and proteins for carbohydrate metabolism, protein biosynthesis, gene expression, plant hormone metabolism (auxin), formation of pollen and biological membrane support, photooxidative damage and temperature stress protection, and resistance to certain pathogen infections (Alloway 2008).

(h) Role of Nickel

Nickel is important for iron absorption and seed germination. Its application on crops prevents certain yield-limiting diseases, and hence results in the significant reduction of pesticide use and promotes crop yield as well. It can also be used as biocontrol for microbial pests, and acts as a key factor for secondary plant metabolites by promoting disease resistance (Wood and Reilly 2007).

10.3 Problems Associated with Nutrient Deficiency in Plants

In the early nineteenth century, Baron Justus von Liebig, a German chemist, showed the essentiality of nutrients for plants' life. He stated, 'We have determined that a number of elements are absolutely essential to plant life. They are essential because a plant deprived of any one of these elements would cease to exist'. He also established the fact that plants obtain their carbon from carbon dioxide in the air, and not from the soil. His theory of 'law of the minimum' states that 'plants will use essential elements only in proportion to each other, and the element that is in shortest supply in proportion to the rest will determine how well the plant uses the other nutrient elements' (Tucker 1999; Reddy 2002).

Generally, all plant problems do not arise because of pests or diseases. A healthy plant requires 16 essential elements to complete its life cycle. Nutrient deficiency usually occurs as leaf discoloration or distortion (Fig. 10.3), reducing flowering and poor fruiting in most of the genus. The goal of farming system is being able to identify these deficiencies.

The occurrence of nutrient deficiencies or toxicities is a result of soil, climatic, crop, and agronomic factors. Such knowledge of soil pH, farming background, and soil texture can be essential for nutrient deficiency predictions (Stevens et al. 2002; Reddy 2012). Moreover, a higher productivity also requires knowing fertilizer rate, application method and time of application, and interaction of these elements with edaphic and environmental factors. It should be kept in mind that many other factors generate similar nutrient deficiency indications, which hamper the visualization and diagnosis. Factors such as inherent plant senescence, aberrant weather (cold, drought), intense sunlight, soil condition (compactness, wet and dry conditions), and also fertilizer burn have resulted in similar indications. However, biotic (disease) stress tends to appear with an asymmetrical pattern, unlikely to nutrient deficiencies where symptoms are distributed or become aligned in a symmetrical pattern over the entire plant (Brown 2013; Wong 2005).

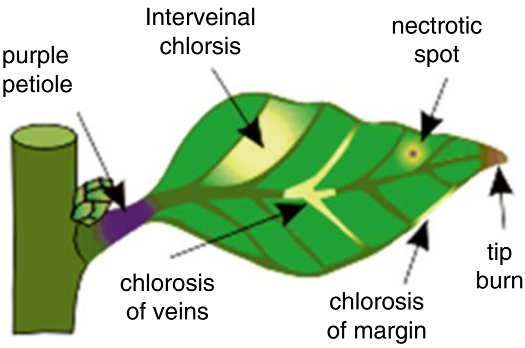

Fig. 10.3 Some common leaf abnormalities resulting from nutrient deficiencies (Reproduced from Flairform 2015)

10.3.1 How to Know a Deficiency?

Visual symptoms are the cheapest diagnostic technique in identifying nutrient stress. However, several other abiotic or biotic stresses hamper identifying features similar to nutrient disorders. There are several steps to identify symptom characterization caused by nutrient stress:

1. Observation of the growth and development pattern when the plant is healthy and has disorder variations.
2. Recognition of plant part affected (new leaves, old leaves, edge of leaf, veins, etc.).
3. Identification of the nature of symptoms: chlorotic, necrotic, or deformed.

Nutrient deficiency is mostly categorized on the basis of whether the symptoms occurred on plant's older leaves or on younger leaves. Any nutrient capable of translocation within plants, such as N, P, K, or Mg, and the symptoms emerged on older leaves is known as 'mobile nutrient'. Immobile nutrients (such as S, Ca, Fe, Cu, Mn, and Zn), which are restricted in movement, are not translocated to the growing region, so younger leaves or apical buds show their deficiency indications first (Reddy 2002).

Table 10.2 Nutrient deficiency and their indicator plants

Deficient nutrient	Indicator plant
Nitrogen	Cauliflower, cabbage, maize, sorghum
Phosphorus	Rapeseed, tomato, lucerne, duranta
Potassium	Potato, banana, cucurbits, cotton, lucerne
Calcium	Cauliflower, cabbage
Magnesium	Potato
Sulphur	Clover, tea, lucerne
Iron	Sugarbeet, gooseberry, acacia, eucalyptus
Manganese	Sugarbeet, oat, potato, citrus
Boron	Sugarbeet, coconut, guava
Zinc	Tomatoes, beans, citrus
Copper	Citrus
Molybdenum	Cauliflower, cabbage

Reproduced from Reddy (2012)

10.3.2 Nutrient Deficiency and Their Visual Symptoms

Plant nutrient deficiency can be observed by some visual symptoms. Most of the symptoms can directly represent the specific nutrient deficiency (Table 10.2).

10.3.2.1 Primary Nutrient Deficiency

10.3.2.1.1 Nitrogen Deficiency

Nitrogen deficiency generally appears in the oldest leaves and lower part and progresses if deficiency is not reversed (Uchida 2000). Low nitrogen content reduced tillering in many cereals and lowers the yield. The plant remains stunted and chlorotic (pale yellow leaves) (Brown 2013). In severe conditions, yellowing of leaf tips and spindly stalks were reported in corn and other small grain cereals. Poor root and secondary shoot development are further related disorders (Sawyer 2004). Nitrogen disorder is normally favoured under poor nitrogenous fertilization, sandy soil, and denitrification process, or in regions of excessive rainfall (Tucker 1999).

10.3.2.1.2 Phosphorus Deficiency

Phosphorus is readily mobilized in plants and their deficient symptoms exist first on older leaves. The plant remains darker green, growth-stunted with reddish purple leaf tips (Fig. 10.4) and margins (Uchida 2000). At temperate areas or whenever soil temperature is less than 60 °F due to heavy wetness or dryness, phosphorus deficiency is also commonly characterized in young plants. In corn hybrid cultivation, although soil is fertile, sometimes phosphorus deficiency may occur due to abrupt changes in soil temperature or moisture level (Sawyer 2004).

10.3.2.1.3 Potassium Deficiency

Lower leaves exhibit chlorosis (lack of greenness) at the margin (Fig. 10.4) and random chlorotic spots that turned into necrotic spots in severe cases (Uchida 2000; Reddy 2012). Poor branching and shoot stunting can also be caused by interaction with other nutrients. Poor grain size in grain crops, leaves scorching of cotton, uneven fruit ripening in tomatoes, and low quality of forage crops (Tucker 1999) are characteristics of phosphorus deficiency.

10.3.2.2 Secondary Nutrients and Plant Growth

10.3.2.2.1 Calcium Deficiency

Calcium deficiency starts from younger leaves, failure of terminal buds, and root tips. As severity occurs, new buds start to die and curl. New leaves turn into white and roots become distorted. 'Blossom-end rot' is the common term of failure of terminal bud observed in tomatoes and peppers. In groundnut, pod development is restricted with poor seed setting (Reddy 2002; Tucker 1999). Low soil pH and excessive soluble salts of aluminium and manganese are more likely causes of phosphorus deficiency.

10.3.2.2.2 Magnesium Deficiency

Interveinal chlorosis (leaves yellowing between the veins) is particularly the common symptom of magnesium deficiency (Fig. 10.5). The deficiency reported under sandy soil in rainfall season is known as 'sand drown' (Tucker 1999; Hosier and Bradley 1999). The symptoms start from older leaves and progress up the plant in severe cases. Older leaves turn into reddish

Fig. 10.4 Deficiency symptoms of phosphorus (**a**), potassium (**b**), and iron (**c**) in corn (Reproduced from Sawyer 2004)

* Magnesium deficiency symptom in leaf, evident from yellow parts of leaf.

** Interveinal chlorosis, a symptom of iron, zinc and manganese deficiencies, evident from yellow parts of leaf.

Fig. 10.5 Micronutrient deficiencies in leaves (Reproduced from Hosier and Bradley 1999)

colour and necrotic spots emerge (Stevens et al. 2002). Tobacco, corn, and forage crops commonly exhibit magnesium deficiency. Also, 'grass tetany' in ruminant animals is caused by magnesium deficiency (Tucker 1999).

10.3.2.2.3 Sulphur Deficiency

Sulphur deficiency symptom is characterized by general yellowing of foliage, similar to nitrogen deficiency. However, the yellowing of leaves begins in younger leaves because sulphur is highly immobilized in plant tissues (Reddy 2012). Delayed maturity and stunted growth are other characteristics of deficiency. Interveinal chlorosis is commonly favoured under sandy or low organic content soil. At acute deficiency, entire plant chlorosis may also occur (Sawyer 2004).

10.3.2.3 Micronutrient Deficiency

10.3.2.3.1 Manganese Deficiency

Manganese (Mn) is relatively immobile in plants. The typical characteristic due to manganese deficiency is interveinal chlorosis in new leaves. Brown patches develop on the leaves of tobacco and reddening occurs in cotton leaves (Fig. 10.5). Yellow stripes run parallel to the leaf blade in the case of corn plants; however, greyish speck formation in the grain is termed as 'grey speck' especially in oat (Tucker 1999; Hosier and Bradley 1999). The problematic soils such as alkaline soils, poorly drained soils, sandy coastal soils, and soil rich in available Fe content can also induce Mn deficiency (Sawyer 2004).

10.3.2.3.2 Zinc Deficiency

Relatively, interveinal chlorosis is an obvious symptom of zinc deficiency (Hosier and Bradley 1999); also, stunted growth and affected plant parts give a rosette-like appearance. Leaves develop into small size, along with short internodes (Reddy 2012). In the acute case, white leaves become rusty brown in colour. In coarse cereal grains (corn and sorghum), whitish band formations occur at the side of the leaf midrib, which is known as 'white bud'. 'Little leaf' in cotton is also common due to zinc deficiency (Tucker 1999; Wong 2005). Zinc deficiency is also favoured by high pH and low soil organic matter, cool or wet soil, and high phosphorous fertilizer application in poor zinc availability of the soil (Wong 2005).

10.3.2.3.3 Iron Deficiency

Iron-deficient plant develops interveinal chlorosis (Figs. 10.4 and 10.5) in leaf growth (Hosier and Bradley 1999). Yellowing or bleaching of newly emerged leaves is quite common (Sawyer 2004; Donohue 2001). Corn rarely shows iron deficiency due to low requirement; however, high soil pH, poorly aerated soil, and calcareous soil favour the iron deficiency (Stevens et al. 2002).

10.3.2.3.4 Copper Deficiency

Chlorotic symptoms without wilting in leaves are considered as a common indicator of copper deficiency. New shoots will not emerge and the whole plant turns into pale green colour. Yellowing of younger leaves, prominent at the start followed by leaf curling, result in 'die-back' symptoms commonly found in small grains (Tucker 1999). In an acute situation, leaves twist and shrivel, and the plant dies prematurely. Oats are reported as the most sensitive crops to copper deficiency and result in 'leaf tip die-back' sickness. High pH soils, compact soils, and soils lacking in nitrogen also favoured copper deficiency (Wong 2005; Reddy 2012).

10.3.2.3.5 Boron Deficiency

The boron-deficient leaves are curled or thickened and have copper structure. Other prominent disorders are the death of growing tips where later shoots deform. Stunted root, poor to set flowers, and the presence of cracked or water-soaked condition in petioles and stems are also included (Reddy 2002). The initial symptoms start with dark rings near the petiole and further progression causes leaf deformation (Tucker 1999). Specific symptoms such as rotting of fruits, tubers or roots, and cork spot in crops such as beets, turnips and potatoes, and apples are also listed in boron deficiency. Twisted stem and poor boll formation also occurred in cotton in the severe absence of boron in the soil (Stevens et al. 2002). Low soil pH below 5.5 or above 6.8 and poor organic matter content especially in sandy soils also induced boron deficiency.

10.3.2.3.6 Molybdenum Deficiency

The plant symptoms of molybdenum deficiency, such as general yellowing, are quite similar to nitrogen deficiency. The whole plant remains pale green to yellow; whiptail leaf formation (top leaves deformed into a shape of whip-like structure) (Tucker 1999) occurs. Marginal chlorosis and mottling along with leaf cupping are other molybdenum deficiency characteristics. Highly podzolized soils and well-drained calcareous soils are also associated with molybdenum deficiency (Stevens et al. 2002).

10.3.3 Indicator Plants

Some plants are more sensitive to certain element content in the soil and can also be used as a diagnostic tool for plant nutrient deficiencies. These plants are commonly termed as 'indicator plants'.

10.4 Nutrient Management Practices by Microbes

Nutrient management practices promote low chemical input into the soil and increase nutrient use efficiency of crops to improve their growth and productivity. Free-living microbes present in the soil have a great impact on nutrient management practices. The major microbial communities that have a significant impact on nutrient management practices are plant growth-promoting rhizobacteria (PGPR), plant growth-promoting fungi (PGPF), actinomycetes, protozoan, and nematodes.

10.4.1 Plant Growth-Promoting Rhizobacteria

PGPR can affect plant growth in either direct or indirect ways. In the direct way, PGPR increase the availability of different nutrients such as P, K, and N, which are essential for plant growth (Glick et al. 2007; Adesemoye et al. 2008), whereas, in the indirect way of plant growth promotion, PGPR prevent plants from harmful effects of one or more deleterious microorganisms. The major processes involved in the indirect way of plant growth promotion are through biocontrol or by antagonism against soil-borne plant pathogens. Specifically, colonization or biosynthesis of antibiotics (Fenton et al. 1999) and other secondary metabolites are considered as major mechanisms involved in the suppression of pathogens. However, the information about the beneficial effects of PGPR on crops is limited and the mechanisms used by PGPR are unclear (Glick 1995).

Inoculation of different PGPR strains such as *Pseudomonas* and *Acinetobacter* resulted in the increased uptake of Fe, Zn, Mg, Ca, K, and P by crop plants (Khan 2005). A significant impact of different PGPR (*P. mendocina* Palleroni) was observed on the uptake of N, P, Fe, Ca, and manganese (Mn) in lettuce (*Lactuca sativa* L. cv. Tafalla) under different water stress conditions (Kohler et al. 2008). Including nutrient management practices, PGPR have also shown an increase in seed germination rate, root growth, yield, leaf area, chlorophyll content, nutrient uptake, protein content, hydraulic activity, tolerance to abiotic stress, shoot and root weights, biocontrol, and delayed senescence (Mahaffee and Kloepper 1994; Raaijmakers et al. 1997; Bashan et al. 2004; Mantelin and Touraine 2004; Bakker et al. 2007; Yang et al. 2009).

While considering nutrient management practices of PGPR, it has been observed that PGPR enhance P availability to the plant, sequestering iron for plant with the help of siderophore production (Bakker et al. 2007). Only a portion of chemical fertilizers is taken up by plants, for example, after applying P into the soil it precipitates and becomes less available to the plants (Gyaneshwar et al. 2002). In 1948, Pikovskaya reported solubilization of insoluble P by microorganisms. Since the 1950s, phosphate-solubilizing bacteria (PSB) are being used as biofertilizer (Kudashev 1956; Krasilinikov 1957). The release of unavailable form of P to available form is an important aspect in terms of soil fertility and plant nutrient availability. There is strong evidence that soil bacteria can convert this unavailable form of P to available form by several mechanisms. As compared to fungi, bacteria are more effective phosphate solubilizers (Alam et al. 2002). Several strains of bacterial species such as *Pseudomonas* and *Bacillus* bacteria (Illmer and Schinner 1992) are reportedly known for their phosphate solubilization ability. Microorganisms enhance the P availability to plants by mineralizing organic P in the soil and by solubilizing precipitated phosphates (Chen et al. 2006; Kang et al. 2002; Pradhan and Sukla 2005). Contribution of PSB among the whole microbial population in the soil is about 1–50 % (Chen et al. 2006). Strains from bacterial genera *Pseudomonas*, *Bacillus*, *Rhizobium*, and *Enterobacter* along with *Penicillium* and *Aspergillus* fungi are the most powerful P solubilizers (Whitelaw 2000). *Bacillus megaterium*, *B. circulans*, *B. subtilis*, *B. polymyxa, B. sircalmous, P. striata*, and *Enterobacter* could be considered as the most important strains (Subbarao 1988; Kucey et al. 1989).

The major portion of P present in the soil is in unavailable organic and inorganic forms, but some bacterial species have mineralization and solubilization potential that can convert this unavailable form of P into bioavailable phosphorus (Hilda and Fraga 2000; Khiari and Parent 2005) (Fig. 10.6). Phosphate solubilization takes place through various microbial processes including organic acid production and proton extrusion (Dutton and Evans 1996; Nahas 1996). PSB secretes organic and inorganic acids that solubilize inorganic P by the action of hydroxyl and carboxyl groups of acids that chelate cations (Al, Fe, Ca) and decrease the pH in basic soils (Kpomblekou and Tabatabai 1994; Stevenson 2005). At the same pH conditions, inorganic acids, for example, hydrochloric acid, are less effective as compared to organic acids (Kim et al. 1997). Therefore, under certain conditions, phosphate solubilization is induced by phosphate starvation (Gyaneshwar et al. 1999). Some strains of *Pseudomonas, Bacillus*, *Enterobacter*, and *Burkholderia* present in the rhizospheric soil were found to produce siderophores and indolic compounds (ICs), which can solubilize phosphate (Ambrosini et al. 2012).

Soil microbes also influence the availability of nitrogen in the soil. For many years, a limited number of bacterial species were believed to be nitrogen fixers (Postgate 1981), but in the last 30 years nitrogen fixation has been shown to be a property with representatives in most of the phyla of Bacteria and also in methanogenic Archaea (Young 1992). Two major families of soil bacteria, namely *Rhizobium* and *Frankia*, are associated with soil N fixation. Another important group of nitrogen-fixing bacteria is cyanobacteria, found in association with a large variety of higher and lower plants, fungi, and algae (Meeks and Elhai 2002). A study on the effect of different strains of *Azotobacter*, *Azospirillum*, *Phosphobacter*, and *Rhizobacter* showed enhanced nitrogen availability to *Helianthus annus* plants, which resulted in increased plant height, number of leaves, stem diameter, seed filling, and seed dry weight (Dhanasekar and Dhandapani 2012). Similarly, potassium-solubilizing bacteria (KSB) such as genera *Bacillus* and *Clostridium* are helpful for the solu-

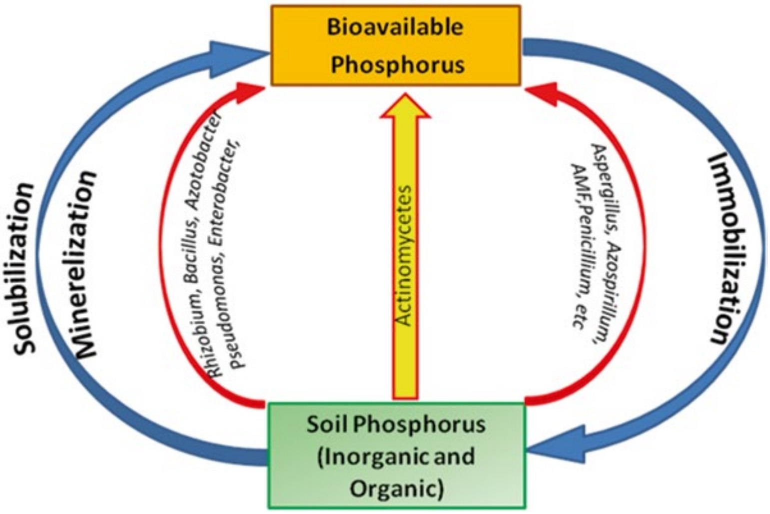

Fig. 10.6 Mobilization and immobilization of phosphorus present in the soil by different soil microbes

bilization and mobilization of potassium from soil to different crops (Mohammadi and Yousef Sohrabi 2012). It has also been reported that including increased availability of P and N, PGPR such as *Pseudomonas* and *Acinetobacter* have a significant impact on the enhanced uptake of Fe, Zn, Mg, Ca, and K (Khan 2005).

10.4.2 Plant Growth-Promoting Fungi

In the last few decades, most studies have focused on the role and interaction of different rhizobacteria, but still the role and mechanism of PGPF are not very well known (Murali et al. 2012). The beneficial effects of certain rhizosphere fungi in terms of plant growth promotion and biological control have been reported by many researchers (Windham et al. 1986; Narita and Suzuki 1991). PGPF are mainly nonpathogenic saprophytes known for their plant growth-promoting property and also for their suppressiveness property against different pathogenic fungi and bacteria of a number of crop plants (Shivanna et al. 1996; Chandanie et al. 2006). The most commonly known PGPF are *Trichoderma* spp. and arbuscular mycorrhizal fungi (AMF).

Trichoderma spp. is most commonly known for its biocontrol potential where it protects plants from different pathogen populations under different soil conditions. In recent years, these fungi have been widely commercially marketed as biopesticides, biofertilizers, and soil amendments. *Trichoderma* spp. also produces numerous biologically active compounds, such as cell wall-degrading enzymes and secondary metabolites (Vinale et al. 2008). The study reports that, after amendment of *T. herzianum* to the soil, a significant improvement in seed germination along with a significant increase in the concentration of Cu, P, Fe, Zn, Mn, and Na was observed in inoculated roots (Yedidia et al. 2001). Another species of *Trichoderma* known for its increased nutrient availability and plant growth-promoting property is *T. viridi* (Srivastava et al. 2006). In recent years, a lot of work has been done to isolate, identify, and characterize different strains of *Trichoderma* spp. to check their availability as PGPF.

PGPF may also improve plant growth indirectly, via alterations to the structure of rhizosphere soil, which benefit the plant. Different fungal strains, namely *Penicillium* sp., *Trichoderma* sp., *Rhizoctonia* sp., and *Pythium* sp., have been reported for their suppressive nature against *S. graminicola.* Pathogen control by PGPF may also occur via niche exclusion, antibiosis, predation, mycoparasitism, and induced systemic resistance (ISR) induction (Murali et al. 2012). Therefore, there is a direct relation of pathogen suppression with plant growth promotion. If there is less pathogen attack in the plant, it will directly improve the plant nutrient availability.

Phosphate solubilization mainly occurs in two ways in soil system: first, by direct solubilization process (Rodriguez and Fraga 1999) and second by the accumulation of P in the form of biomass of microorganisms (Oehl et al. 2001). There are two ways in microbial P solubilization: by solubilization processes and from P accumulation in the biomass of microorganism. The important genera of PSF are *Aspergillus* (Vassilev et al. 2007) and some species of *Penicillium* (Oliveira et al. 2009). *Penicillium oxalicum* isolated from the rhizosphere of rock phosphate mine showed a significant impact in solubilizing rock phosphate rather than promote the growth of wheat and maize. The most important feature of PSF is that they do not lose their activity during subculturing under laboratory conditions (Kucey 1983). Therefore, these microbes can be isolated from any source and grown under laboratory conditions for further application in the field for phosphate solubilization. The solubilization of P in soil depends on the availability of rock P in the soil. If higher concentration of rock P occurs in the soil, it increases the solubilization process.

Trichoderma spp. is known for its high activity for the solubilization of inorganic-bound phosphate into available form. The mechanism so far discussed for this solubilization process is that this unavailable form of phosphorus might accumulate inside fungal body for cellular processes and this sequestration of P in fungal mycelium results in the depletion of P in nearby areas, but after the lysis of mycelium with age, this phosphorus is released into the soil and readily available to the plants (Kapri and Tewari 2010). Ejikeme and Anyanwu (2013) reported that the efficiency of solubilization of tricalcium phosphate (TCP) by PSF is related to reduction in pH due to the secretion of organic acids excreted by PSF (Sharma et al. 2012). Including phosphate solubilization, *A. niger* and *P. glaucum* are also known for nitrogen fixation in the soil. The investigations of Jodin and Hallie carried out as early as the 1960s led them to believe that fungi possessed the power to fix nitrogen.

In the scientific world, AMF are known as one of the most promising fungi in terms of increased nutrient uptake by plants and for increasing soil fertility. The arbuscular mycorrhizal (AM) symbiosis between fungi and plant roots is the most common type of interaction in the rhizosphere (Smith and Read 1997). AM is one of the oldest symbioses formed by plants. Phosphate absorption by plants is explained under two different pathways: the “direct” uptake pathway at the plant–soil interface through root epidermis and root hairs, and the “mycorrhizal” uptake pathway via fungal mycelium (Smith et al. 2003). Much of the inorganic phosphate applied to soil as a fertilizer is rapidly converted to unavailable forms with low solubility. Soluble P is released from insoluble phosphates by a variety of solubilization reactions involving rhizosphere microorganisms (Kapoor et al. 1989).

Mycorrhizal plants can take up more phosphorus than non-mycorrhizal plants, mainly from the same soluble phosphate pool (Fig. 10.7). Soluble phosphate released by the activity of phosphate-solubilizing microorganisms (PSM) can be actively taken up by mycorrhizal roots (Kapoor et al. 1989).

Mycorrhiza is known for its functioning in phosphorus uptake and it encodes a phosphate transporter gene that plays a key role in this mechanism. The process of phosphate transport from the mycorrhiza to the plant has been studied previously by identifying a complementary DNA (cDNA) that encodes a transmembrane phosphate transporter termed GvPT from *G. versiforme* (Harrison and Van Buuren 1995). In recent years, several phosphate transporter genes have been identified and characterized for their involvement in different uptake pathways. Shin et al. (2004) reported that two Pht1 transporters, which are normally expressed at the root periphery, after loss of function in *Arabidopsis*, exhibited a strong reduction of phosphate uptake by 75 %.

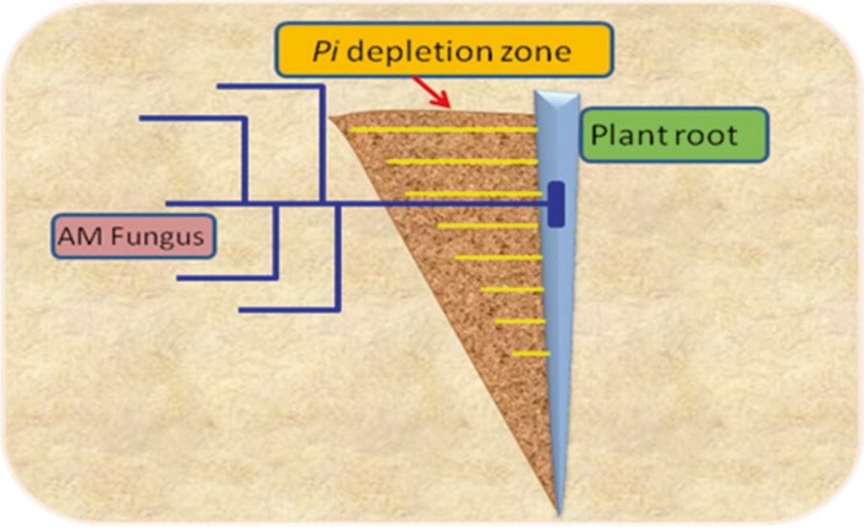

Fig. 10.7 Phosphate depletion zone in growing plant and its management by AMF (Reproduced from Karandashov and Bucher 2005)

In the AM symbiosis, firstly, fungal hyphae interact with plant roots through aspersorium followed by phosphate uptake by the fungus from the soil and then transfer to the root. Two phosphate transporter genes, namely GvPT and GiPT from *G. versiforme* and *G. intraradices*, respectively, are predominantly expressed in the extraradical fungal mycelium that encodes proteins, which are likely to participate in phosphate uptake at the fungus–soil interface (Harrison and Van Buuren 1995; Maldonado-Mendoza et al. 2001). The mechanisms involved in the release of phosphate from the fungus to colonized plant cells are presently unknown, but it is believed that phosphate ions pass through periarbuscular membrane (PAM) inside plant roots and probably because of concentration gradient their transfer through the membrane could be facilitated by ion-specific carriers, pumps, or channels (Karandashov and Bucher 2005).

In mycorrhizal plants, P uptake per unit root length is two to three times higher than in nonmycorrhizal plants (Tinker et al. 1992). However, as soil available P levels increase, benefits to plant growth decrease because the plant can directly take P from the soil without the need of mycorrhizae mycelia. Few reports on mycorrhiza and its role in increased Zn and Cu uptake by both maize (Kothari et al. 1990) and soybean (Lambert and Weidensaul 1991) are also present. Therefore, AMF has a significant role in rhizospheric soil and it shows a positive impact on plant nutrition in soil systems where low plant available nutrient levels are present. The fungus supplies the plant with water and nutrients such as phosphate, while the plant provides fungus with photosynthetically produced carbohydrates.

10.4.3 Actinomycetes

Actinomycetes are known as the most successful microbial source for all types of bioactive metabolites, including the agroactive type. During 1988–1992, over 1000 secondary metabolites from actinomycetes were discovered. *Streptomyces* is reported as a major genus that produces these compounds. In the past 5 years, about 60 % of the new insecticides and herbicides originated from *Streptomyces* (Tanaka and Omura 1993). It is also estimated that as many as three-quarters of all *Streptomyces* species are capable of antibiotic production (Alexander 1977). Actinomycetes have antifungal, antitumour, and immunosuppressive activities. These activities are associated with the production of a variety of antibiotics with diverse chemical structures such as polyketides, b-lactams, and peptides in addition to a variety of other secondary metabolites produced by different species of actinomycetes (Behal 2000).

Despite the role of actinomycetes as a biocontrol agent, these microbes are also known for their capacity to enhance plant growth (Aldesuquy et al. 1998). Only few studies have been carried out on the species of genus *Streptomyces* investigating their potential as PGPR. This is surprising, as streptomycetes is generally present in abundance in soil microflora and effectively colonizes plant root system, but at the same time it is also able to endure unfavourable growth conditions by forming spores (Alexander 1977).

Only a few studies on plant growth-promoting role of streptomycetes have been reported so far. The study by Merriman et al. (1974) reported the use of a *S. griseus* (Krainsky). Waksman and Henrici isolate as a seed treatment of barley, oat, wheat, and carrot, in order to increase their growth. Marketable yields were increased over controls by 17 and 15 % in two separate field trials. Specifically, both trials also indicated an increased yield of large and very large grade carrots over controls (Merriman et al. 1974). These strains were isolated and screened for their biocontrol activity against *Rhizoctonia solani*, but, in addition to this, these isolates are also increasing the plant growth. Therefore, a correlation can be established between the biocontrol activity and plant growth promotion. This can be explained as an indirect correlation between biocontrol agents and plants. As an active biocontrol agent, these microbes reduce the activity of pathogen and, on the other hand, they also provide a suitable environment for the plant to increase their nutrient availability from rhizosphere soil.

10.4.4 Other Microbes

Including PGPR, PGPF, and actinomycetes, there are few other microbes such as protozoan and nematodes that are present in the soil in a smaller proportion, but having a significant impact on plant growth and plant protection from different harmful agents present in the soil.

10.4.4.1 Nematodes

Nematodes respond rapidly to the disturbance and enrichment of their environment. Increased microbial activity in the soil leads to changes in the proportion of opportunistic bacterial feeders in a community. Nematodes are important in mineralizing, or releasing, nutrients in plant-available forms. When nematodes eat bacteria or fungi, ammonium ($NH4^+$) is released because bacteria and fungi contain much more nitrogen than the nematodes require. Over time, the enrichment opportunists are followed by more general opportunists that include fungal feeders and different genera of bacterial feeders (Bongers and Ferris 1999). This succession of nematode species plays a significant role in the decomposition of soil organic matter, mineralization of plant nutrients, and nutrient cycling (Ingham et al. 1985; Hunt et al. 1987; Griffiths 1994).

The feeding habit of nematodes is dependent on the C:N ratio. The results concluded that bacteria- or fungi-feeding nematodes either have higher or on par C:N ratio than host (Ferris et al. 1997; Chen and Ferris 1998). Most of the carbon (nearly 40 %) in C:N ratio utilized for metabolic activities (Ingham et al. 1985) and the released by-products of consumption as ammonia in the soil (Rogers1969) is found to be beneficial to microbes and plant uptake. The rate of nutrient cycling such as nitrogen cycle considerably varies depending on the behavior of microbivorous nematodes.

Such nematodes are also considered as environmental purity indicators. Any changes in soil fertility and pollutants can be assessed by studying nematode activities. In addition, immediate changes in decomposition process or particular nutrient status have also shown considerable changes in nematode activities and work as different indices (Bongers and Ferris 1999).

10.4.4.2 Protozoa

Soil protozoan genera have an intensive role, deciding the nutrient mineralization especially of nitrogen availability. As compare to bacterial cell, protozoa having poor concentration of nitrogen in their body. However, because protozoa have a feeding habit similar to nematodes, a certain amount of nitrogen will be released in soil as ammonia that is utilized by soil microbes and plant uptakes. Bacterial growth and colonization are also regulated when such protozoa feed and stimulate their population. Hence, soil aggregation and organic decomposition are also facilitated. Protozoa are also considered as feed to other microfauna, which helps in the suppression of many diseases as competition to them.

10.5 Conclusion

So far, nutrient deficiency in the soil is made up by the direct application of fertilizer, but in recent years, researchers are focusing on soil nutrient management practices through different soil microbes, because most of the time nutrients are already present in the soil, but their availability to the plants is very less or none. Rhizospheric microbes can help to overcome the problem of nutrient unavailability or its deficiency to the plants. It is important to comprehend the aspects of useful microbes and implement its application to modern agricultural practices. The new technology developed using the powerful tool of molecular biotechnology can enhance the biological pathways of the production of phytohormones. If identified and transferred to the useful microbes, these technologies can help in relief from environmental stresses. However, there is lack of awareness among the farmers, ecologists, and agriculturists for the application of these beneficial microbes in the field. To fill this gap between research laboratories and field application of beneficial microbes, there is a need for a better understanding of these microbes, their mechanism, functioning, application, and their sustainability, so that it can ultimately reach the agricultural field.

Overall, plant nutrients play different roles and may reduce disease incidence in certain cases or increase them in others, depending on particular nutrients, the host plant, and other factors. The role of beneficial microbes for the management of these nutrients in plants cannot be denied, and recent advancement in technologies helps us to understand the mechanism, functioning, and role of these microbes in nutrient management. An appropriate management of nutrients is essential to achieve healthy plants, and this is a significant benefit to the environment. Therefore, to achieve this important multidisciplinary goal, there is a need for joint research between different streams of science.

References

Arnon DI, Stout PR (1939) The essentiality of certain elements in minute quantity for plant with special reference to copper. Plant Physiol 14(2):371–375

Adesemoye AO, Torbert HA, Kloepper JW (2008) Enhanced plant nutrient use efficiency with PGPR and AMF in an integrated nutrient management system. Can J Microbiol 54:876–886

Aktas H, Karni L, Chang DC, Turhan E, Bar-Tal A, Aloni B (2005) The suppression of salinity associated oxygen radicals production, in pepper (*Capsicum annuum* L.) fruit, by manganese, zinc and calcium in relation to its sensitivity to blossom- end rot. Physiol Plant 123:67–74

Alam S, Khalil S, Ayub N, Rashid M (2002) In vitro solubilization of inorganic phosphate by phosphate solubilizing microorganism (PSM) from maize rhizosphere. Int J Agric Biol 4:454–458

Aldesuquy HS, Mansour FA, Abo- Hamed SA (1998) Effect of the culture filtrates of Streptomyces on growth and productivity of wheat plants. Folia Microbiol 43:465–470

Alexander M (1977) Introduction to soil microbiology, 2nd edn. Krieger Publishing Company, Malabar, p 467

Allen VB, Pilbeam DJ (2007). Handbook of plant nutrition. CRC Press, New York, p 4. ISBN 978-0-8247-5904-9

Alloway BJ (2008) Zinc in soils and crop nutrition. IFA/IZA, Paris/Brussels

Aloni B, Karni L, Deventurero G, Turhan E, Aktas H (2008) Changes in ascorbic acid concentration, ascorbate oxidase activity, and apoplastic pH in relation to fruit development in pepper (*Capsicum annuum* L.) and the occurrence of blossom end rot. J Hortic Sci Biotechnol 83:100–105

Ambrosini A, Beneduzi A, Stefanski T, Pinheiro F, Vargas L, Passaglia L (2012) Screening of plant growth promoting Rhizobacteria isolated from sunflower *Helianthus annuus* L. Plant Soil 356:245–264

Anza M, Riga P, Garbisu C (2005) Time course of antioxidant responses of *Capsicum annuum* subjected to progressive magnesium deficiency. Ann Appl Biol 146:123–134

Bakker PAHM, Pieterse CMJ, van Loon LC (2007) Induced systemic resistance by fluorescent *Pseudomonas* spp. Phytopathology 97:239–243

Barlog P, Grzebisz W (2004) Effect of timing and nitrogen fertilizer application on winter oilseed rape (*Brassica napus* L.). II. Nitrogen uptake dynamics and fertilizer efficiency. J Agron Crop Sci 190:314–323

Bashan Y, Holguin G, de-Bashan LE (2004) Azospirillum-plant relationships: physiological, molecular, agricultural, and environmental advances (1997–2003). Can J Microbiol 50:521–577

Behal V (2000) Bioactive products from Streptomyces. Adv Appl Microbiol 47:113–157

Bongers T, Ferris H (1999) Nematode community structure as a bioindicator in environmental monitoring. Trends Ecol Evol 14(6):224–228

Brown SH (2013) Plant nutrient deficiencies in ornamental plants of South Florida. University of Florida, IFAS Extension. http://lee.ifas.ufl.edu/Hort/GardenHome.shtml. Accessed 15 Jan 2015

Cakmak I (1994) Activity of ascorbate-dependent H_2O_2-scavenging enzymes and leaf chlorosis are enhanced in magnesium and potassium-deficient leaves, but not in phosphorus-deficient leaves. J Exp Bot 45:1259–1266

Cakmak I, Marschner H (1992) Magnesium deficiency and high light intensity enhance activities of superoxide dismutase, ascorbate peroxidise and glutathione reductase in bean leaves. Plant Physiol 98:1222–1227

Candan N, Tarhan L (2003) Relationship among chlorophyll-carotenoid content, antioxidant enzyme activities and lipid peroxidation levels by Mg^{2+} deficiency in the *Mentha pulegium* leaves. Plant Physiol Biochem 41:35–40

Chandanie WA, Kubota M, Hyakamachi M (2006) Interaction between arbuscular mycorrhizal fungus *Glomus mosseae* and plant growth promoting fungus Phoma sp. on their root colonization and growth promotion of cucumber (*Cucumis sativus*). Mycoscience 46:201–204

Chen JA, Ferris H (1998) Nitrogen mineralization by *Aphelenchus avenae* associated with *Rhizoctonia* sp. and barley straw. J Nematol 29:572

Chen YP, Rekha PD, Arunshen AB, Lai WA, Young CC (2006) Phosphate solubilizing bacteria from subtropical soil and their tricalcium phosphate solubilizing abilities. Appl Soil Ecol 34:33–41

Dhanasekar R, Dhandapani R (2012) Effect of biofertilizers on the growth of *Helianthus annuus*. Int J plant Ani Environ Sci 2:143–147

Donohue SJ (2001) Conditions contributing to various plant nutritional deficiencies. Crop and soil environmental news. Virginia Cooperative Extension, Blacksburg

Dutton VM, Evans CS (1996) Oxalate production by fungi: its role in pathogenicity and ecology in the soil environment. Can J Microbiol 42:881–895

Ejikeme OC, Anyanwu UC (2013) Comparative study on solubilization of tri-calcium phosphate (TCP) by phosphate solubilizing fungi (PSF) isolated from Nsukka pepper plant rhizosphere and root free soil. JYFR 4:52–57

Fenton TE, Brown JR, Mausbach MJ (1999) Effects of long-term cropping on organic matter content of soils: implications for soil quality. In: Lal R (ed) Soil quality and soil erosion. CRC Press, Boca Raton, pp 95–124

Ferris H, Venette RC, Lau SS (1997) Population energetics of bacterial feeding nematodes: carbon and nitrogen budgets. Soil Biol Biochem 29:1183–1194

Flairform (2015) Nutrient deficiency symptoms. http://www.flairform.com/hints/nutrient_deficiency.htm. Accessed 10 Jan 2015

Glick BR (1995) The enhancement of plant growth by free living bacteria. Can J Microbiol 41:109–117

Glick BR, Todorovic B, Czarny J, Cheng Z, Duan J, McConkey B (2007) Promotion of plant growth by bacterial ACC deaminase. Crit Rev Plant Sci 26:227–242

Griffiths BS (1994) Microbial feeding nematodes and protozoa in soil: their effects on microbial activity and nitrogen mineralization in decomposition hotspots and the rhizosphere. Plant Soil 164:25–33

Gyaneshwar P, Parekh LJ, Archana G, Podle PS, Collins MD, Hutson RA, Naresh KG (1999) Involvement of a phosphate starvation inducible glucose dehydrogenase in soil phosphate solubilization by Enterobacter asburiae. FEMS Microbiol Lett 171:223–229

Gyaneshwar P, Kumar GN, Parekh LJ, Poole PS (2002) Role of soil microorganisms in improving P nutrition of plants. Plant Soil 245:83–93

Halliwell B (1987) Oxidative damage, lipid peroxidation and antioxidant protection in choroplasts. Chem Phys Lipids 44:327–340

Harrison MJ, Van Buuren ML (1995) A phosphate transporter from the mycorrhizal fungus *Glomus versiforme*. Nature 378:626–629

Hilda R, Fraga R (2000) Phosphate solubilizing bacteria and their role in plant growth promotion. Biotech Adv 17:319–359

Hosier S, Bradley L (1999) Guide to symptoms of plant nutrient deficiencies. http://ag.arizona.edu/pubs/garden/az1106.pdf. Accessed 13 Jan 2015

Huang ZA, Jiang DA, Yang Y, Sun JW, Jin SH (2004) Effects of nitrogen deficiency on gas exchange, chlorophyll fluorescence, and antioxidant enzymes in leaves of rice plants. Photosynthetica 42:357–364

Hunt HW, Coleman DC, Ingham ER, Ingham RE, Elliott ET, Moore JC, Rose SL, Reid CPP, Morley CR (1987) The detrital food web in a shortgrass prairie. Biol Fert Soils 3:57–68

Illmer P, Schinner F (1992) Solubilization of inorganic phosphates by microorganisms isolated from forest soil. Soil Biol Biochem 24:389–395

Ingham RE, Trofymow JA, Ingham ER, Coleman DC (1985) Interactions of bacteria, fungi and their nematode grazers: Effects on nutrient cycling and plant growth. Ecol Monogra 55:119–140

Kang SC, Hat CG, Lee TG, Maheshwari DK (2002) Solubilization of insoluble inorganic phosphates by a soil-inhabiting fungus *Fomitopsis* sp. PS 102. Curr Sci 82:439–442

Kapoor KK, Mishra MM, Kukreja K (1989) Phosphate solubilization by soil microorganisms: a review. Indian J Microbiol 29:119–127

Kapri A, Tewari L (2010) Phosphate solubilization potential and phosphatase activity of rhizospheric *Trichoderma* spp. Braz J Microbial 41:787–795

Karandashov V, Bucher M (2005) Symbiotic phosphate transport in arbuscular mycorrhizas. Trends Plant Sci 10:22–29

Kato MC, Hikosaka K, Hirotsu N, Makin A, Hirose T (2003) The excess light energy that is neither utilized in photosynthesis nor dissipated by photoprotective mechanisms determines the rate of photoinactivation in photosystem II. Plant Cell Physiol 44:318–325

Khan AG (2005) Role of soil microbes in the rhizospheres of plants growing on trace metal contaminated soils in phytoremediation. J Trace Elem Med Biol 18:355–364

Khiari L, Parent LE (2005) Phosphorus transformations in acid light-textured soils treated with dry swine manure. Can J Soil Sci 85:75–87

Kim KY, Jordan D, McDonald GA (1997) Solubilization of hydroxyapatite by *Enterobacter agglomerans* and cloned *Escherichia coli* in culture medium. Biol Fert Soils 24:347–352

Kohler J, Hernandez JA, Caravaca F, Roldan A (2008) Plant growth promoting rhizobacteria and arbuscular mycorrhizal fungi modify alleviation biochemical mechanisms in water-stressed plants. Funct Plant Biol 35:141–151

Kothari SK, Marschner H, Romheld V (1990) Direct and indirect effects of VA mycorrhiza and rhizosphere microorganisms on mineral nutrient acquisition by maize (*Zea mays* L.) in a calcareous soil. New Phytol 116:637–645

Kpomblekou K, Tabatabai MA (1994) Effect of organic acids on release of phosphorus from phosphate rocks. Soil Sci 158:442–453

Krasilinikov NA (1957) On the role of soil microorganism in plant nutrition. Microbiologiya 26:659–672

Kucey RMN (1983) Phosphate solubilizing bacteria and fungi in various cultivated and virgin Alberta soils. Can J Soil Sci 63:671–678

Kucey RMN, Janzen HH, Legget ME (1989) Microbial mediated increases in plant available phosphorus. Adv Agron 42:199–228

Kudashev IS (1956) The effect of phosphobacterin on the yield and protein content in grains of Autumm wheat, maize and soybean. Doki Akad Skh Nauk 8:20–23

Kumar AM, Soll D (2000) Antisense HEMA1 RNA expression inhibits heme and chlorophyll biosynthesis in arabidopsis. Plant Physiol 122:49–56

Lambert DH, Weidensaul TC (1991) Element uptake by mycorrhizal soybeans from sewage-sludge-treated soil. Soil Sci Soc Amer J 55:393–397

Mahaffee WF, Kloepper JW (1994) Applications of plant growth promoting rhizobacteria in sustainable agriculture. In: Pankhurst CE, Doube BM, Gupta VVSR, Grace PR (eds) Soil biota: management in sustainable farming systems. CSIRO, Melbourne, pp 23–31

Maldonado-Mendoza IE et al (2001) A phosphate transporter gene from the extra-radical mycelium of an arbuscular mycorrhizal fungus *Glomus intraradices* is regulated in response to phosphate in the environment. Mol Plant-Microbe Interact 14:1140–1148

Mamatha N (2007) Effect of sulphur and micronutrients (iron and zinc) on yield and quality of cotton in a vertisol. Department of Soil Science and Agricultural Chemistry College of Agriculture. Dharwad University of Agricultural Sciences, Dharwad

Mantelin S, Touraine B (2004) Plant growth-promoting bacteria and nitrate availability: impacts on root development and nitrate uptake. J Exp Bot 55:27–34

Marschner H (1995) Mineral nutrition of higher plants, 2nd edn. Academic, New York

Meeks JC, Elhai J (2002) Regulation of cellular differentiation in filamentous cyanobacteria in free-living and plant associated symbiotic growth states. Microbiol Mol Biol Rev 66:94–121

Mehta CM, Palni U, Franke-Whittle IH, Sharma AK (2014) Compost: its role, mechanism and impact on reducing soil-borne plant diseases. Waste Manage 34(3):607–622

Mengel K, Kirkby EA (2001) Principles of plant nutrition, 5th edn. Kluwer Academic Publishers, Dordrecht

Merriman PR, Price RD, Kollmorgen JF, Piggott T, Ridge EH (1974) Effect of seed inoculation with *Bacillus subtilis* and *Streptomyces griseus* on the growth of cereals and carrots. Aust J Agric Res 25:219–226

Mohammadi K, Yousef Sohrabi Y (2012) Bacterial biofertilizers for sustainable crop production: a review. J Agric Biol Sci 7:307–316

Murali M, Amruthesh KN, Sudisha J, Niranjana SR, Shetty HS (2012) Screening for plant growth promoting fungi and their ability for growth promotion and induction of resistance in pearl millet against downy mildew disease. J Phytol 4:30–36

Nahas E (1996) Factors determining rock phosphate solubilization by microorganism isolated from soil. World J Microbiol Biotechnol 12:18–23

Narita Y, Suzuki T (1991) Influence of sterile dark, mycelial fungus on take-all of wheat. Ann Phytopath Soc Jpn 57:301–305

Oehl F, Oberson A, Probst M, Fliessbach A, Roth HR, Frossard E (2001) Kinetics of microbial phosphorus uptake in cultivated soiIs. Biol Fert Soils 34:31–41

Oliveira CA, Alvesb VMC, Marrielb IE, Gomesb EA, Scottia MR, Carneiro NP et al (2009) Phosphate solubilizing microorganisms isolated from rhizosphere of maize cultivated in an oxisol of the Brazilian *Cerrado Biome*. Soil Biol Biochem 41:1782–1787

Palta JP (2000) Stress interactions at the cellular and membrane levels. Hort Sci 25(11):1377

Pikovskaya RI (1948) Mobilization of phosphorus in soil in connection with vital activity of some microbial species. Microbiology 17:362–370

Postgate J (1981) Microbiology of the free-living nitrogen fixing bacteria, excluding cyanobacteria. In: Gibson AH, Newton WE (eds) Current perspectives in nitrogen fixation. Elsevier/North-Holland Biomedical, Amsterdam, pp 217–228

Prabhu AS, Fageria ND, Huber DM, Rodrigues FA (2007) Potassium and plant disease. In: Datnoff LE, Elmer WE, Huber DM (eds) Mineral nutrition and plant disease. APS Press, St. Paul, pp 57–78

Pradhan N, Sukla LB (2005) Solubilization of inorganic phosphate by fungi isolated from agriculture soil. Afr J Biotechnol 5:850–854

Raaijmakers JM, Weller DM, Thomashow LS (1997) Frequency of antibiotic-producing *Pseudomonas* spp. in natural environments. Appl Environ Microbiol 63:881–887

Raven JA, Evans MCW, Korb RE (1999) The role of trace metals in photosynthesis electron transport in O2 evolving organisms. Photosynth Res 60:111–149

Reddy SR (2002) Mineral nutrition, manures and fertilizers. In: Reddy SR (ed) Principles of agronomy, 1st edn. Kalyani Publishers, New Delhi, pp 183–193

Reddy SR (2012) Principles of crop production, 4th edn. Kalyani Publishers, New Delhi

Rodriguez H, Fraga R (1999) Phosphate solubilizing bacteria and their role in plant growth promotion. Biotech Adv 17:319–339. doi:10.1016/S0734-9750(99)00014-2

Rogers WP (1969) Nitrogenous components and their metabolism: Acanthocephala and Nematoda. In: Florkin M, Scheer BT (eds) Chemical zoology, vol III. Academic, New York, pp 379–428

Roy RN, Finck A, Blair GJ, Tandon HLS (2006) Plant nutrients and basics ofplant nutrition. In: Plant nutrition for food security. A guide for integrated nutrient management. Food and Agriculture Organization of the United Nations, Rome, pp 25–33

Sawyer J (2004) Nutrient deficiencies and application injuries in field crops. IPM 42, revised July 2004. Iowa State University Extension, Ames

Sharma A, Rawat US, Yadav BK (2012) Influence of phosphorus levels and phosphorus solubilizing fungi on yield and nutrient uptake by wheat under subhumid region of Rajasthan, India. ISRN Agronomy Article ID 234656, 9 p

Shaul O (2002) Magnesium transport and function in plants: the tip of the iceberg. Biometals 15:309–323

Shin H et al (2004) Phosphate transport in Arabidopsis: Pht1;1 and Pht1;4 play a major role in phosphate acquisition from both low- and high-phosphate environments. Plant J 39:629–642

Shivanna MB, Meera MS, Hyakumachi M (1996) Role of root colonization ability of plant growth promoting fungi in the suppression of take-all and common root rot of wheat. Crop Prot 15:497–504

Smith SE, Smith FA, Jakobsen I (2003) Mycorrhizal fungi can dominate phosphate supply to plant irrespective of growth responses. Plant Physiol 133:16–20

Smith SE, Read DJ (1997) Mycorrhizal symbiosis. Academic, London

Srivastava SN, Singh V, Awasthi SK (2006) *Trichoderma* induced improvement in growth, yield and quality of sugarcane. Sugar Tech 8:166–169

Stevens G, Motavalli P, Scharf P, Nathan M, Dunn D (2002) Crop nutrient deficiencies and toxicities. In: Integrated nutrient management. Plant protection programs, University of Missouri Extension. Available via DIALOG. http://extension.missouri.edu/main/DisplayCategory.aspx?C=1#publications. Accessed 12 Jan 2015

Stevenson FJ (2005) Cycles of soil: carbon, nitrogen, phosphorus, sulfur, micronutrients. Wiley, New York

Subbarao NS (1988) Phosphate solubilizing micro-organism. In: Subbarao NS (eds) Biofertilizer in agriculture and forestry. Regional Biofertilizer Development Centre, Hissar, pp 133–142

Tanaka Y, Omura S (1993) Agroactive compounds of microbial origin. Annu Rev Microbiol 47:57–87

Tewari RK, Kumar P, Tewari N, Srivastava S, Sharma PN (2004) Macronutrient deficiencies and differential antioxidant responses-influence on the activity and expression of superoxide dismutase in maize. Plant Sci 166:687–694

Tewari RK, Kumar P, Sharma PN (2006) Magnesium deficiency induced oxidative stress and antioxidant responses in mulberry plants. Sci Hortic 108:7–14

Tinker PB, Jones MD, Durall DM (1992) A functional comparison of ecto- and endomycorrhizas. In: Read DJ, Lewis DH, Fitter AH, Alexander IJ (eds) Mycorrhizas in ecoystems. CAB International, Wellingford, pp 303–310

Tucker MR (1999) Essential plant nutrients: their presence in North Carolina soils and role in plant nutrition. Agronomic Division, NCDA & CA October, pp 1–9

Turhan E, Karni L, Aktas H, Deventurero G, Chang DC, Bar–Tal A, Aloni B (2006) Apoplastic anti-oxidants in pepper (*Capsicum annuum* L.) fruit and their relationship to blossom end rot. J Hortic Sci Biotechnol 81:661–667

Uchida R (2000) Essential nutrients for plant growth: nutrient functions and deficiency symptoms. In: Plant nutrient management in Hawaii's soils, pp 31–55

Vassilev N, Vassileva M, Bravo V, Fernandez-Serrano M, Nikolaeva I (2007) Simultaneous phytase production and rock phosphate solubilization by *Aspergillus niger* grown on dry olive wastes. Ind Crop Prod 26:332–336

Vinale F, Sivasithamparam K, Ghisalberti EL, Marra R, Woo SL, Lorito M (2008) Trichoderma–plant-pathogen interactions. Soil Biol Biochem 40:1–10

Waraich EA, Ahmad R, Ashraf MY, Saifullah AM (2011) Improving agricultural water use efficiency by nutrient management in crop plants. Acta Agric Scand Sect B Plant Soil Sci 61(4):291–304

Welch RM (2002) The impact of mineral nutrients in food crops on global human health. Plant Soil 247:83–90

Whitelaw MA (2000) Growth promotion of plants inoculated with phosphate solubilizing fungi. Adv Agron 69:99–151

Wilkinson S, Clephan AL, Davies WJ (2001) Rapid low tempeature induced stomatal closure occurs in cold tolerant *Commelina cummunis* leaves but not in cold sensitive tobacco leaves, via a mechanism that involves apoplastic calcium but not abscisic acid. Plant Physiol 126:1566–1578

Windham MT, Elad Y, Baker R (1986) A mechanism for increased plant growth induced by *Trichoderma* sp. Phytopathology 76:518–521

Wong M (2005) Visual symptoms of plant nutrient deficiencies in nursery and landscape plants, Soil and Crop Management. SCM 10. Cooperative Extension Service, University of Hawaii, Manoa

Wood BW, Reilly CC (2007) Interaction of nickel and plant diseases. In: Datnoff LE, Elmer WH, Huber DM (eds) Mineral nutrition and plant disease. American Phytopathological Society Press, Minneapolis, pp 217–247

Yang J, Kloepper JW, Ryu C-M (2009) Rhizosphere bacteria help plants tolerate abiotic stress. Trends Plant Sci 14:1–4

Yedidia I, Srivastava AK, Kapulnik Y, Chet I (2001) Effect of *Trichoderma harzianum* on microelements concentration and increased growth of cucumber. Plant Soil 235:235–242

Young P (1992) Phylogenetic classification of nitrogen-fixing organisms. In: Stacey G, Burris RH, Evans HJ (eds) Biological nitrogen fixation. Chapman and Hall Inc, New York, pp 43–86

Zaharieva TB, Abadia J (2003) Iron deficiency enhances the level of ascorbate, glutathione, and related enzymes in sugar beet roots. Protoplasma 221:269–275

Ziaeian AH, Malakouti MJ (2001) Effects of Fe, Mn, Zn and Cu fertilization on the yield and grain quality of wheat in the calcareous soils of Iran. In: Horst WJ et al (eds) Plant nutrition, food security and sustainability agro-ecosystems, Springer Netherlands, vol 92, pp 840–841