Role of Soil Phosphorus on Legume Production

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Abstract

Legumes play a significant role in sustainable agriculture through their ability to improve soil fertility and health. Legumes, with a mutual symbiotic relationship with some bacteria in soil, can improve nitrogen (N) amount through biological N-fixation (BNF). But to maximize such functions, legumes need more phosphorus (P) as it is required for energy transformation in nodules. Besides, P also plays a significant role to root development, nutrient uptake, and growth of legume crops. But most of the agricultural soils have inadequate amounts of P to support efficient BNF as it exists in stable chemical compounds which are least available to plants. The deficiency of P causes significant yield reduction in leguminous crops. The mineral P sources are nonrenewable, unlike N. So there is a need to enhance P use efficiency (PUE) for better legume productivity and soil sustainability. Improving the PUE of applied fertilizer requires enhanced P acquisition from the soils by crops for growth and development. It is necessary to better exploit soil P resources through increasing labile soil P using leguminous crops in a rotation cycle. Moreover, incorporation of legumes in cropping system with better P management under P-deficient conditions could be a promising tool for improving legume productivity. Endowed with inherent potential PUE, deep root system, root exudate-mediated P-solubilization, and nutrient-rich residues, legumes can improve soil fertility and enhance the soil profile and efficient nutrient cycling. The data obtained from various research studies show that agriculturally important legumes can fix 40–60 million metric tons of N annually. In view of this importance of P, this chapter emphasizes on the PUE and its role in legume production for food security programs, soil sustainability, and management.

Keywords

Biological nitrogen fixation · Legume · Nodulation · Phosphorus

Abbreviations

ADP	Adenosine diphosphate
ATP	Adenosine triphosphate
BNF	Biological nitrogen fixation
INM	Integrated nutrient management
MAP	Monoammonium phosphate
N	Nitrogen
OM	Organic matter
P	Phosphorus
PSB	Phosphorus solubilizing bacteria
PUE	Phosphorus use efficiency
SIFS	Sustainable integrated farming systems
SOM	Soil organic matter
SOP	Soluble organic phosphorus

15.1 Introduction

Legume crops is a major part of sustainable integrated farming systems (SIFS) as they fix atmospheric nitrogen (N) (Korir et al. 2017; Suzaki et al. 2015). The practice of including legumes in cropping system plays a key role to increase soil fertility through symbiotic N-fixation. Legumes induce N-fixing bacteria in some genera, viz., *Rhizobium*, *Sinorhizobium*, *Mesorhizobium*, and *Bradyrhizobium* (Berg 2009; Fenchel 2011; Meena et al. 2017, 2018). Cultivation of leguminous crops can be an alternative source of nutrients as it is a renewable and eco-friendly source of N (Oldroyd and Dixon 2014). But some biotic and abiotic factors disturb the symbiotic relationship between legumes and bacteria with negative effects on its productivity (Udvardi and Poole 2013) and stressful events such as drought, low and high pH, salinity, extreme temperatures, heavy metal problems (Zahran 1999; Dimkpa et al. 2009; Xie et al. 2009; Meena et al. 2015b). Among the nutrients, deficiency of phosphorus (P) in soil has an adverse impact on legume production as it is required for energy transformation in nodules and enhanced N-fixation (Rotaru and Sinclair 2009; Udvardi and Poole 2013; Yadav et al. 2017). The P is a primary nutrient essential for plant growth and development and important for regulation of various enzymatic activities and constituent for energy transformation (Schulze et al. 2006). Some molecules which contain P include nucleic acids, proteins, lipids, sugars, and adenylate and are required for the functioning of plant cells (Zhang et al. 2014). The P also plays a significant role in many metabolic processes including energy generation, respiration, membrane synthesis and its integrity, nucleic acid synthesis, photosynthesis, activation or inactivation of enzymes, signaling, and carbohydrate metabolism (Vance et al. 2003; Zhang et al. 2014). Therefore, P- deficient soil and low availability impose major restrictions on the vegetative and reproductive growth development of crop (Vance et al. 2003; Zhang et al. 2014). The P constraint directly decreases photosynthesis through its negative effects on vegetative crop growth of leaf area development and photosynthetic ability per unit leaf area (Vance et al. 2003; Sulieman et al. 2013). Likewise, inadequate supply of P can also affect carbon (C) absorption and distribution between plant shoots and its underground parts (Zhang et al. 2014). The P also plays a crucial role in the development of the symbiotic relationship between legumes and bacteria as a certain amount of P is required to carry out biological nitrogen fixation (BNF) (Oliveira et al. 2002; Rotaru and Sinclair 2009). There is considerable evidence that nodulated legumes require more P than nonsymbiotic plants grown solely on a mineral N source (Rotaru and Sinclair 2009; Sulieman and Schulze 2010).

A large amount of P is required for metabolic pathways of energy transfer that takes place during nodule functioning (Hernandez et al. 2009; Cabeza et al. 2014a, b). But most of the agricultural soils have inadequate amounts of P to support efficient BNF (Brown et al. 2013). The inadequacy of P in soil is mainly due to its retention as adsorbed P on the surface of soil particles and associated with amorphous aluminum (Al) and iron (Fe) oxides (Mitran and Mani 2017). About 90% of the inorganic P fertilizers are used in agriculture crop production produced from high-grade rock phosphates which expected to be depleted shortly within 30–50 years (Abrol and Palaniappan 1988; Cordell and Drangert 2009). So there will be possibilities of less vegetative growth and production of legumes as P availability expected to decrease shortly as the growth of the N-fixing legumes severely affected under P-deficient condition due to poor nodule functioning (Sulieman and Tran 2015; Dhakal et al. 2016). So there is a need to improve P resources to better legume crop productivity and soil sustainability through increasing PUE in legumes. There are some adaptive strategies which can also help to conserve the supply of P under the deficient condition and enhance N-fixation. The objective of this chapter is to evaluate the potential role of P in legume productivity as well as pointing out some adaptive strategies to improve PUE in the deficient soil and enhance BNF and productivity of legumes.

15.2 Importance of Phosphorus in Legumes

The P is a vital component of adenosine diphosphate (ADP) and adenosine triphosphate (ATP) the "energy unit" (Cabeza et al. 2014a, b; Nesme et al. 2014). These are high-energy phosphate compounds that control most processes in legume crops including respiration, photosynthesis, nucleic acid synthesis, and protein and plant cell formation through nutrient transport (Sawyer 1947; Nesme et al. 2014; Meena et al. 2014). ATP formed during photosynthesis has P in its structure and processes from the beginning of seedling growth to the formation of grain and maturity (Nesme et al. 2014). The specific growth factors that have been associated with P in legume crops are the following (Fig.15.1):

- It's essential for commercial seed productions.
- It promotes the root growth of leguminous crops.
- It helps to early maturity in legumes.

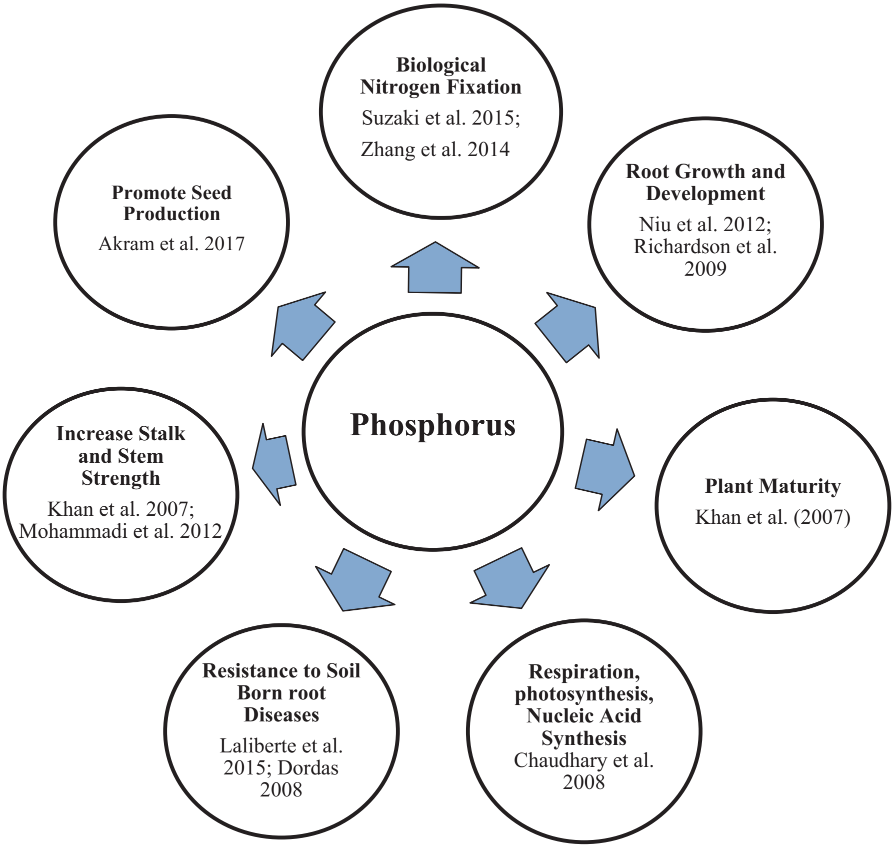

Fig. 15.1 Role of P in legumes

- It enhances the stalk strength in vegetative stage of legumes.
- It promotes the resistance to soil born root rot diseases.
- It stimulates root development in legumes.

15.3 Impact of Phosphorus Deficiency in Legumes

The BNF takes place in root nodules which are the outgrowths induced by N-fixing rhizobial bacteria (Fenchel 2011). However, such symbiotic relationship is dramatically affected by various biotic and abiotic factors (Schulze 2004) and stressful events such as drought, low and high pH, salinity, extreme temperatures, heavy metal problems.

Low P availability is affecting the legume production in most of the soils (Lopez-Arredondo et al. 2014; Schulze et al. 2006). The supply and availability of P are very important as it's a major component for N transformation and regulation of enzymatic activities to enhance BNF (Vance et al. 2003; Zhang et al. 2014). The P plays key roles in metabolic processes related to the aboveground organs, glycolysis, including energy generation, nucleic acid synthesis, respiration, and photosynthesis of legume crops (Chaudhary et al. 2008). The limited availability of P in soil leads to poor plant growth and development of legume crops. P deficiency has some negative effects on BNF, nodule formation, and photosynthetic ability in leaf and hence reduces photosynthesis (Sulieman and Schulze 2010; Sulieman et al. 2013; Yadav et al. 2017). The legume crops have more demand for P for optimal N-fixation compared to non-modulating plants like cereals because of P having a crucial role in nodule energetic transformations (Roatru 2009). A number of researchers observed a significant correlation between P concentration in nodule and N-fixation (Schulze et al. 2006; Rotaru and Sinclair 2009; Cabeza et al. 2014a, b). The metabolic pathways such as N-fixation that occur in bacteroids, as well as the ammonium assimilation into amino acids and ureides that occur in the plant cell fraction of nodules, require a large amount of P in energy transfer during nodule functioning (Sulieman and Tran 2015). In the absence of optimum supply of P, the growth of the legumes severely retards, and nodules are not sufficient to support the requirements for plant growth and development (Hernandez et al. 2009; Sulieman and Tran 2015). Studies revealed that up to 20–25% of total plant P was estimated to be allocated to nodule fraction (Jebara et al. 2005; Kouas et al. 2005). Tang et al. (2001) observed that under the P-deficient situation, even much higher P is preferentially partitioned to the nodules for maintaining N-fixation. The efficient P allocation and proper usage of available P in nodules during P limitations are very much essential for the optimal symbiotic interaction between the host plant and its rhizobial partner (Kouas et al. 2005; Al-Niemi et al. 1997; Meena et al. 2017). Hence, the P allocation rate may play an important role in the determination of the symbiotic efficiency as well as the degree of legume adaptability under deficient nutritional conditions (Sulieman and Tran 2015).

15.4 Phosphorus Cycle in Legume-Cultivated Soil

P can be applied to the soil in the form of manures, fertilizers, plant residues, and agricultural wastes, municipal and industrial by-products, etc. (Fig. 15.2). The native sources of P in soil are primary P minerals (apatite) and secondary clay minerals, i.e., calcium (Ca), Fe, Al-phosphates, which also play a significant role in maintaining the buildup of available P in soil through dissolution and desorption process (Mitran and Mani 2017). Within the soil, organic forms of phosphate such as living soil biomass, soil organic matter (SOM), and soluble organic P (SOP) can be made available to plants by bacteria that break down organic matter (OM) to inorganic forms of P; this process is known as mineralization (Meena et al. 2018). Processed plant and animal products, such as manure or compost, have been reported to have lower P use efficiency than that of water-soluble P mainly applied in the form of fertilizers (McLaughlin and Alston 1986; Nachimuthu et al. 2009; Oberson et al. 2010). Soil solution P ($H_2PO_4^-$ and HPO_4^{-2}) can be immobilized to

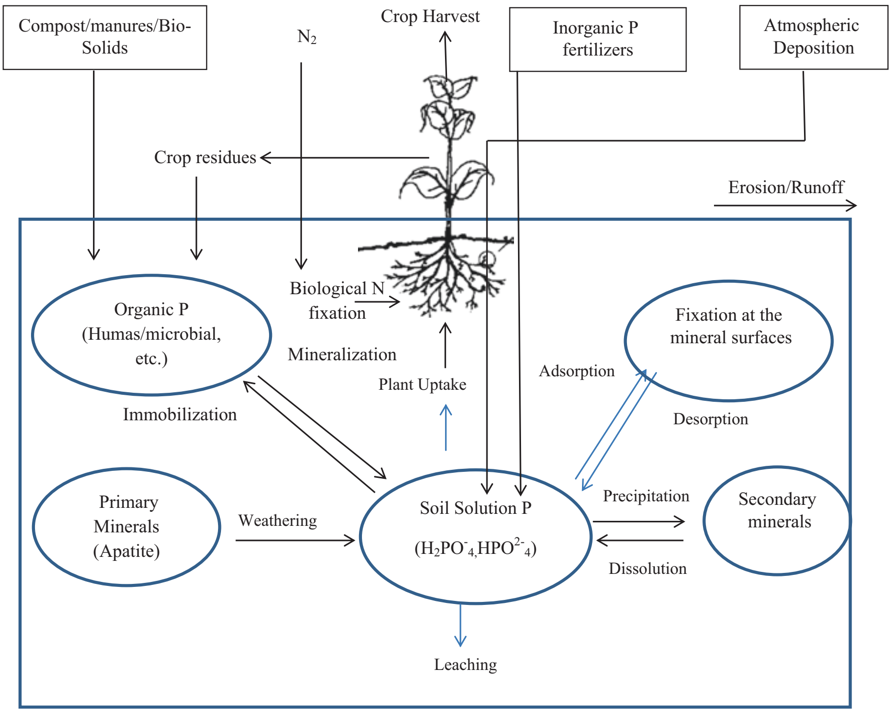

Fig. 15.2 Phosphorus cycle in legume-cultivated soils

organic P or adsorbed on the surface of soil particles and associated with amorphous Al and Fe oxides and become unavailable to plants (Ohel et al. 2004). The inherent soil properties and climate condition also affect the crop growth and response of crops to applied P fertilizers. Climatic parameters such as rainfall, temperature, etc. and soil attribute like soil temperature, aeration, salinity, etc. also affect the rate of P mineralization (NRCS, USDA). The long-term application of P inputs (inorganic P fertilizer, manure, compost) have effects on an available P due to release and erosion losses resulting eutrophication in water bodies and low land agriculture (Ulen et al. 2007; Meena et al. 2015c). Although P doesn't readily leach out from the root zones; the potential for P loss is mainly associated with erosion and runoff (Farkas et al. 2013). But integrated nutrient management (INM) in legume field has the potential to increase PUE and decrease soil P losses and efficiently uptake by the crops (Ali et al. 2002; Mitran and Mani 2017; Dhakal et al. 2016). At the same time, it should be aimed at replenishing SOM content, optimizing soil biological activity, and minimizing erosion and water runoff that support to increase PUE (Schroder et al. 2010; Spiess 2011). There are several mechanisms by which legumes can adapt to low P availability such as by activating high-affinity orthophosphate ion transporters for taking up P or by releasing organic acids which solubilize P bound to Ca and by releasing phosphatase enzymes to hydrolyze organic P compounds

(George et al. 2011; Richardson et al. 2011). The legume crops are colonized by phosphorus solubilizing bacteria (PSB) and able to access the P in plant available from within rhizospheric zone (Morel and Plenchette 1994; Meena et al. 2018). The enhanced uptake of P promotes biological nitrogen fixation and enriches N content in the soil which in turn influences growth and yield of legume crops.

15.5 Sources of Available Phosphorus for Leguminous Crops

A number of phosphatic fertilizers (Table 15.1) are available based on their solubility (Ghosal and Chakraborty 2012). The available phosphate can be defined by their solubility either in water or in neutral or alkaline ammonium citrate (Ghosal and Chakraborty 2012). It varies from country to country; some are using water to extract available P from fertilizer or by dissolving it in citrate or both. These definitions are not always adequate for evaluation of fertilizer availability for alkaline and calcareous soils. In calcareous soil, where pH is in the higher range, water solubility of P is hindered (Leytem and Mikkelsen 2005). Some of the highly water-soluble phosphate fertilizers are monocalcium phosphates, phosphoric acids, ammonium ortho- and polyphosphates, etc., whereas calcium metaphosphates, di- and tricalcium phosphates, and basic slag are not soluble in water but are citrate soluble (MacKay et al. 1990; Yadav et al. 2017). Apatites are major components of source rock phosphate that are insoluble even in ammonium citrate (Chien et al. 2011). Phosphatic fertilizers are either ordinary superphosphate (approximately 16% P_20_5) or concentrated superphosphate (43–46% P_20_5 approximately); both are predominantly monocalcium phosphates (Ca $[H_2P0_4]_2$) with relatively small amounts of iron and aluminum phosphates and dicalcium phosphate ($CaHP0_4$). Orthophosphoric acid as a phosphate (55% P_20_5) fertilizer is very effective in calcareous and alkaline soils where the Ca content is large enough to prevent undesirable acidification. The

Table 15.1 Sources of phosphate fertilizer

P fertilizer	P_20_5%
Water soluble	
Superphosphate (ordinary)	16–20
Superphosphate (concentrated)	40–45
Monoammonium phosphate	61
Diammonium phosphate	46
Insoluble	
Apatite (rock phosphate)	20–30
Bone meal	18–20
Citrate soluble	
Dicalcium phosphate	35–40
Basic slag	3–5

Data sources: Ghosal and Chakraborty (2012) and Chien et al. (2011)

solubility of ammonium phosphate fertilizers is higher than superphosphate fertilizers. The N and P content of fertilizer grade monoammonium phosphate (MAP) and diammonium phosphate (DAP) is approximately 12% and 18% N and 61% and 46% P_20_5, respectively. These fertilizers are industrially attractive having a high nutrient content, the low tendency for caking, and low hygroscopicity. Whereas the nitric phosphate fertilizers are highly hygroscopic and citrate soluble which contains 4–13% P and 14–20% N. The nitric phosphate fertilizers are effective in neutral, alkaline, and calcareous soils as a P source to plants is a function of the ratio of water- to citrate-soluble phosphate. The nitric phosphates with a low water solubility are considered unsuitable in calcareous, neutral, and alkaline soils (Venkateswarlu et al. 1970; Sharma and Singh 1976; Bijay et al. 1976).

15.6 Phosphorus Use Efficiency in Legumes

The PUE is low in agriculture soils. When P is applied to the soil through a source of fertilizer or organic manure, it undergoes several biochemical reactions which remove phosphate ions from the soil solution (Kruse et al. 2015). It is measured that only 15–30% of applied fertilizer P is taken up by crops in the year of its application (Swarup 2002; Syers et al. 2008). However, the remaining 70–90% becomes part of the soil P pool, which is fixed but subsequently released to the crop over the following months and years (Roberts and Johnston 2015). Improving the PUE for growth in legume crops requires enhanced P acquisition from the soil and enhanced use of P in processes that lead to faster growth and a greater allocation of biomass to the harvestable parts (Kruse et al. 2015). In biomass calculations, measurements are often restricted to the aboveground portion of plant parts in leguminous crops. The PUE is the amount of total biomass produced per unit of P uptake (Hammond et al. 2009; Varma and Meena et al. 2016). Intraspecies and large genotypic differences for PUE are well known for different legumes such as cowpea (*Vignaunguiculata* L.; Sanginga et al. 2000), soybean (*Glycine max* L.; Furlani et al. 2002; Jemo et al. 2006), faba bean (*Vicia faba* L.; Daoui et al. 2012), and common bean (*Phaseolus vulgaris* L.; Vadez et al. 1999).

15.7 Role of Phosphorus in Legume Production

15.7.1 Growth, Root Development, and Nutrient Uptake in Legumes

Continuous cultivation of crops or following mono-cropping sequence without field fallowing shows a severe deficiency of most of the major and micro nutrients especially N, P, and zinc (Abbasi et al. 2008). The major nutrient demand for N in a deficient soil is normally achieved by the use of chemical fertilizers. However, the high cost of mineral N fertilizers and their unavailability at the time of requirement are the two major constraints responsible for low fertilizer N inputs. This

Table 15.2 Potential roles of P on N-fixation in legumes

Sl. no.	Role	References
1	Increasing top and root growth of legume plants	Zahran (1999) and Zafar et al. (2011)
2	Decreasing time needed for active nodule development	Tang et al. (2001)
3	Increasing the size and number of nodules	Hayat et al. (2008), Korir et al. (2017) and Kasturikrishna and Ahlawat (1999)
4	Increasing the amount of N assimilated nodules per unit weight	Sulieman et al. (2013) and Schulze et al. (2006)
5	Act as ingredients for *Rhizobium* bacteria to convert atmospheric N to ammonium	Berg (2009), Fenchel (2011) and Suzaki et al. (2015)
6	Promotes translocation of photosynthate from leaves to root and the movement of N-containing compound from nodules to another plant part	Zahran (1999) and Vance et al. (2003)
7	Controlling key enzyme reactions and regulate metabolic pathways	Rotaru and Sinclair (2009), Zhang et al. (2014) and Hernandez et al. (2007)

emphasizes the importance of developing an alternative means to meet the demand of nutrients (especially N and P) in plants through the use of beneficial bacteria in the ecosystem that is sustainable ergonomically, environmentally friendly, and affordable (Souza et al. 2015; Meena et al. 2016). As most of the nutrients are poorly available or may deficient, the efficient utilization of such from the soil by root is a major concern (Buerkert et al. 2001). The rate of root growth, an extension of root hairs, and the plasticity of root architecture are very much important for effective exploration of soil and interception of nutrients (Richardson et al. 2009). The recent studies indicated that P enhanced root system which provides greater root-soil contact and eventually higher uptake of P and other important and low mobility nutrients and absorption of higher concentration of mineral nutrients (Zafar et al. 2011) (Table 15.2). Almost all the legumes required P in relatively large amounts for growth and have been reported to promote leaf area, biomass, yield, nodule number, and nodule mass (Kasturikrishna and Ahlawat 1999). P supplement in legumes has great potential for promoting growth and higher yield, increases nodule number, as well as enhances symbiotic establishment for increased N-fixation (Ndakidemi et al. 2006). Several studies have reported the important role of P in growth and production of legumes in many tropical soils (Buerkert et al. 2001; Ohyama 2010; Kisinyo et al. 2012). The low availability of P in the bulk soil limits plant uptake. So there is a need to study how beneficial bacteria and P application can affect the uptake of nutrients in leguminous crops (Ndakidemi et al. 2011; Olivera et al. 2004) reported that the application of P significantly increased root and shoot P concentration (six- and fourfold, respectively) and nodule biomass (fourfold) in common bean (*Phaseolus vulgaris* L). Makoi et al. (2013) reported that *Rhizobium* inoculation significantly increases the uptake of P, potassium (K), magnesium (Mg), zinc (Zn), Fe, and Ca in different plant organs. Weisany et al. (2013) reported that the leguminous crops take up small amounts of nutrients relatively in the early season, but as they grow, the nutrient uptake increases. The *Bradyrhizobium* inoculants have been developed and are primarily used for supplying N to plants, and inoculation enhances the uptake of P, K, S, Mn, Fe Ca, Mg, B, Cu, Mo, and Zn in leguminous plants. A number of researchers have reported that the application of P fertilizers and inoculation with *Bradyrhizobium* significantly enhanced nodulation, shoot biomass, and grain yield and improve symbiotic nitrogen fixation of mash bean crop (Zaman et al. 2008; Vance 2001; Meena et al. 2017).

15.7.2 N-Fixation in Legumes

The atmospheric N gas concentration is ~80% and mostly unusable by living organisms. All the living organisms including plants, animals, and microorganism need N for the synthesis of proteins, nucleic acid, amino acid, and other necessary nitrogenous compound necessary for life (Ohyama 2010). The N deficiency in the soil causes death of plants, animals, and microorganisms as they are not able to use atmospheric N. BNF is the process that changes inert N to biologically useful NH_3 to the plants. This process is mediated in nature only by the bacteria. Legumes have a mutual symbiotic relationship with some N-fixing bacteria in the soil which can improve levels of N in the plant root zone (Ghosh et al. 2007; Peoples et al. 1989; Dhakal et al. 2016). In a natural ecosystem and a cropping system, legume can fix N in the soil in the range of 30–180 kg/ha (Frankow-Lindberg and Dahlin 2013). A common soil bacterium, *Rhizobium*, invades the root and multiplies within the cortex cells. During development of the bacteria, plant provides all the essential nutrients and energy for the bacteria (Fenchel 2011; Suzaki et al. 2015). After a couple of weeks of infection, small nodules are visible depending on legume species and germination conditions. Hayat et al. (2008) observed less than 100 nodules per plant in beans and several hundred nodules per plant in soybean and may have 1000 or more nodules on a well-developed peanuts plant.

Peanut nodules are white or gray in color and not able to fix atmospheric N usually. With the progress of growing period, the nodules become pink or reddish in color, indicating N-fixation has started. The pink or red color is caused by leg hemoglobin which contains both iron and molybdenum that controls oxygen flow to the bacteria. P is one of the important ingredients for *Rhizobium* to convert atmospheric N to ammonium (NH_4) which can be used by plants. P influences nodule development through its basic functions in plants as an energy source when 16 molecules of ATP are converted to ADP as each molecule of N is reduced to NH_3 (Berg 2009). The translocation of photosynthate from leaves to root and the movement of N-containing compound from nodules to other plant part are vital to an efficient symbiotic system (Zahran 1999; Meena et al. 2017). The number of researchers across the worlds has reported increased N-fixation in legumes by adding phosphate to the P-deficient soil (Ahlawat and Ali 1993; Bekere and Hailemariam 2012).

Hayat et al. (2008) observed 26% and 30% higher nodules in green gram (*Vigna radiata* (L) and black gram (*Vingna mungo* (L) crop, respectively, due to P fertilization over non-fertilized beans. The significant role of P in the symbiotic N-fixation process could be summarized by the following:

- Increase top and root growth of legume plants.
- Enhance early formation of active nodules for benefitting from hosting legumes.
- Increase the size and number of nodules.
- Improve the amount of N assimilated nodules per unit weight.
- Total amount of N increasing in the harvested portion of the host legume plants.
- Rhizobia bacteria in surrounding of soil, it helps in improving the root of density of crop plants.

The P supplements and *Rhizobium* inoculation is important to the soil fertility because of its potential for excellent N-fixation by increasing nodulation in legumes (Zhang et al. 2014; Bedoussac et al. 2015; Suzaki et al. 2015). The incorporation of legumes in cereal-based cropping system significantly enriches the N content in soil by BNF from the atmosphere and improved subsequence crop yield and productivity of soils (Liu et al. 2011; Zhang et al. 2014; Bedoussac et al. 2015; Ram and Meena 2014). Among all the essential nutrients required by plants, N is one of the most crucial elements, and deficiency of it causes significant yield reduction in the agricultural crop in all types of soil (Shah et al. 2003; Bedoussac et al. 2015). Hence, application of nitrogenous fertilizers is essential for optimum crop productivity for most of the crops. Due to continuous removal of N by intense cereal mono-cropping system, soil's capacity to supply the quantities of N required for optimum yield is declining rapidly (Layek et al. 2014a; Bedoussac et al. 2015). Continuous application of costly N fertilizers cannot subside the effect alone. Therefore, N fertilizer must be supplemented with rotations utilizing legumes break crops which can increase supply and availability of N through BNF (Layek et al. 2014b). Cultivation of various varieties or cultivars of grain legumes for BNF has become one of the most attractive strategies for the development of sustainable agricultural systems (Hardarson 1993; Shiferaw et al. 2004). The legume residues to subsequent crops can fix N through the decomposition and mineralization process (Hara 2001; Fatima et al. 2007; Shu-Jie et al. 2007; Dhakal et al. 2016). Because of relatively high N content and low C:N ratio, legume residues can supply more mineral N to the succeeding crops than that of cereal residues (Lynch et al. 2016). However, the N in leguminous crop residues is only partially available to plants during the first growing season (Wagger 1989; Stevenson and Kessel 1997) and gradually transferred from the labile pool to more stabilize C pools in soil (Hassink and Dalenberg 1996). Hence, legumes are playing a significant role for sustaining soil health by solubilizing insoluble P in soil, improving the soil physical environment, increasing soil microbial activity, and restoring organic matter (Ghosh et al. 2007; Layek et al. 2014a; Bedoussac et al. 2015).

15.7.3 Productivity of Legumes

The P is involved in various functions in growth and metabolism in legumes (Hernandez et al. 2007). It is frequently a major limiting nutrient for plant growth including legumes in most of the tropical soils. Thus, application of an optimum dose of P fertilizer has a significant influence on improving growth and productivity of legume crops. Along with synthetic fertilizers, PSB could also play an important role in increasing P availability by solubilizing the fixed P and supplying it to plants in a more available form (Khan et al. 2007). Srinivasarao et al. (2007) reported that among the kharif (rainy season) pulses, pigeon pea (*Cajanus cajan*) having dominant deep-rooted system performs extremely well under rainfed conditions and responds significantly to applied P in all type of soils with low available P status. They have also reported that application of 80 kg P_2O_5 ha^{-1} in pigeon pea significantly increased seed yield by 29.2% over control in Northern Indian soils, whereas in Central India, the soil produces maximum yield when applied with P at the rate of 90 kg P_2O_5 ha^{-1} which 54.6% higher was over control (Table 15.3). In a study, Singh and Ahlawat (2007) reported that application of 30 kg ha^{-1} P_2O_5 increased seed yield of pigeon pea approximately up to 1300 kg ha^{-1}, but *Rhizobium* inoculation with this P level increased the yield up to 1800 kg ha^{-1}. A similar result has also been reported by other researchers (Singh and Ahlawat 2007; Meena et al. 2014). Srinivasarao et al. (2007) reported that response of black gram to applied P at a different region of India varies from 60 to 90 kg P_2O_5 ha^{-1}. Dhillon and Vig (1996) suggested that if the available P status in the soil was low to medium, the response of green gram to applied P was found up to 40 kg P_2O_5 ha^{-1} while it was only 20 kg P_2O_5 ha^{-1} in soil testing high in available P. They have also found that the degree of response of lentil to applied P depended to a great extent on available P status of the soil. As per All India Coordinated Research Project (AICRP 1999) report, the response of chickpea to applied P was observed up to 60 kg P_2O_5 ha^{-1} (Table 15.3).

But the degree of response varied from region to region. Similarly, growth attributes of cowpea (*Vigna unguiculata*) such as plant height, leaf area, the number of branches, and the number of leaves were significantly increased by the application

Table. 15.3 Impact of phosphorus fertilization on yield of legumes

SL. no.	Legume crop	P dose (P_2O_5 kg ha^{-1})	Yield response	References
1	Pigeon pea (*Cajanus cajan*)	80–90	29.2–54.6% increment in yield over control	Srinivasarao et al. (2003)
2	Pigeon pea (*Cajanus cajan*)	30	Yield up to 1300 kg ha^{-1}	Singh and Ahlawat (2007)
3	Black gram (*Vigna mungo*)	60–90	Optimum yield	Srinivasarao et al. (2007)
4	Green gram (*Vigna radiata*)	40	Optimum yield	Dhillon and Vig (1996)
5	*Phaseolus* beans (*Phaseolus vulgaris*)	150	62% increase in seed yield	Ruschel et al. (1982)

of phosphorus fertilizer (Krasilnikoff et al. 2003; Nyoki et al. 2013). Ndakidemi and Dakora (2007) attributed this to the fact that phosphorus is required in large quantities in the shoot and root tips where metabolism is high, and cell division is rapid. P application has significantly improved yield and yield attributes of cowpea varieties, as it is utilized the applied P fertilizer judiciously in growth and development processes. This is in conformity with the findings of several workers (Okeleye and Okelana 2000; Natare and Bationo 2002; Ndakidemi and Dakora 2007; Singh et al. 2011) who also discovered a significant increase in yield of cowpea in response to phosphorus application. Application of phosphorus did not only increase cowpea yield but rather enhanced nodulation and phosphorus content of leaf and stem over the without application of P (Agboola and Obigbesan 2001). In Kenya, fertilizing Phaseolus beans with 150 kg/ha of P increased seed yield by 62% and increased nitrogen fixation from an average of 8–60 kg/ha. In an experiment with green gram in Pakistan, increasing the P fertilizer rate from 25 to 35 kg P/ha resulted in an increase in N fixation from 20 to 48 kg/ha (Ruschel et al. 1982).

15.8 Benefits of Phosphorus Supplementation in Legumes

Grain legumes are being popularized throughout the globe at an increasing level due to their vast use in different situations including human food, animal feed, as well as industrial demands (Zhang et al. 2011; Bedoussac et al. 2015). Considering the increasing needs for human consumption of plant proteins (pulses) and the economic constraints of applying fertilizer in legumes, there is a major role for grain legumes in cropping systems, especially in regions where affordability of fertilizer is difficult (Ndakidemi and Dakora 2003). Grain legumes such as soybean (*Glycine max*), cowpea, and common bean (*Phaseolus vulgaris*) have the potential to grow in different agroecological zones (Yagoub et al. 2012). Legumes are economically important crops used in a wide range of products like tortillas, chips, doughnuts, bread, spreads, and types of snacks or liquid form of yogurt and milk and thus play a significant role in the sustainability of agricultural systems (Das and Ghosh 2016; Meena et al. 2015d). BNF is becoming more attractive, environmentally friendly, and economically viable N inputs and acts as a substitute of inorganic fertilizers for resource-poor farmers (Bekere and Hailemariam 2012). Most tropical soils experience low N, which is the major constraint in crop production. Small-scale agriculture which is practiced in most sub-Saharan Africa covers the majority of the people, of which chemical fertilizers are unaffordable because of increasing prices in each year (Tadele 2017). Intercropping of cereals and legumes and crop rotation with legumes has found to be alternative sources and means of improving the fertility of the soil and boost crop productivity and farmer's income (Ndakidemi and Dakora 2003; Zhang et al. 2011; Layek et al. 2014a; Meena et al. 2015a). Several studies have shown that BNF incorporates residual N in the soil which adds OM nutrients for the next cropping season to cereal crops as well as other legumes (Zahran 1999; Lithourgidis et al. 2006, 2011). The BNF is therefore considered to have economic and ecological environmental benefits (Ndakidemi and Dakora 2003; Bedoussac et al. 2015). The nutrient supply in crop production is one of the key components to higher yields (Gehl et al. 2005). The per capita consumption of fertilizer in Tanzania is standing at 8 kg ha^{-1} as compared with 52 kg ha^{-1} for South Africa and Zimbabwe and 27 kg ha^{-1} for Malawi (Walter 2007; Gyaneshwar et al. 2002). The combined application of bacterial inoculants and P fertilizer to field legume plants significantly increased biomass production and grain yield as compared with the single use of N and P or rhizobial strains alone (Ndakidemi et al. 2006). From the economic analysis, the increase in grain yield with inoculation translated into a significantly higher marginal rate of return and profit for soybean and common bean farmers in Tanzania (Ndakidemi et al. 2006). In view of increasing price of fertilizers, it seems the cost of nutrients will be increasing in most cropping systems (Komareka et al. 2017). Evidently, legumes will remain the component of the farming system in remote areas comprised of poor farmers due to their capacity to fix N. Research efforts should be directed in assessing the optimum combinations between organic and inorganic fertilizers along with legume incorporation in cropping system that will offer immediate economic returns to the resource-poor farmers who cannot afford the full package of inorganic fertilizers (Chhonkar 2002; Yadav et al. 2013).

15.9 Adaptive Strategies to Overcome P Deficiency for Better N-Fixation and Legume Productivity

There is a need to develop some adaptive strategies which can help to conserve the supply of P under the deficient condition and enhance legume productivity (Veneklaas et al. 2012; Meena et al. 2015d). The adaptive response of nodule metabolism to P deficiency is crucial to improving symbiotic efficiency under P-deficient situations (Esfahani et al. 2014). There are a number of adaptive strategies (Fig. 15.3) such as P-homeostasis in nodule, increasing P acquisition, upgrading N-fixation per unit of nodule mass, and consumption per unit of nodule mass which compensate for the reduction in the number of nodules (Vance et al. 2003; Lopez-Arredondo et al. 2014; Sulieman and Tran 2015). However, the molecular mechanism is including maintenance of the P-homeostasis in nodules for rhizobia-legume symbiosis emerging as a main adaptive strategy for P-deficient soil (Sulieman and Tran 2015).

The main concept of such strategies is to conserve more P concentration in the nodule which can maintain a high rate of N-fixation (Graham 1992; Nogales et al. 2002; Dhakal et al. 2016). There are several ways to P stabilization in the symbiotic tissues such as including higher P allocation to nodules, the formation of a strong P sink in nodules, direct P acquisition via nodule surface and P remobilization from organic-P containing products (Sulieman and Tran 2015). Several studies have shown that symbiotic N-fixation could continue without any disturbance if total plant P is estimated to be allocated toward nodule up to 20% (Jebara et al. 2005; Tajini et al. 2009). Nodules represent a preferential strong sink for P incorporation during P starvation among the other plant parts (Le Roux et al. 2008; Hernandez

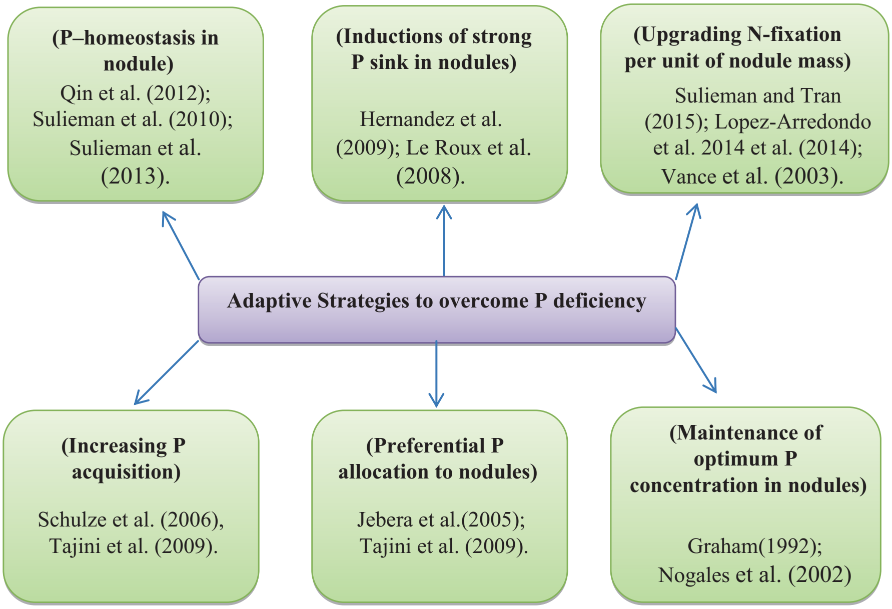

Fig. 15.3 Adaptive strategies to overcome P deficiency for better N-fixation and legume productivity

et al. 2009). Formation of cluster root and mycorrhizas also plays a key role in N-fixation by increasing root surface area and exudation of an organic acid and hence enhanced P acquisition during low P supply (Schulze et al. 2006; Tajini et al. 2009). Remobilization of organic P within the plant by encoding acid phosphatase (Qin et al. 2012; Zhang et al. 2014) is also an important biochemical and physiological adaptive strategy to P deficiency.

15.10 Conclusions

Legumes are becoming integral parts of the farming system because of its capabilities of atmospheric N-fixation through a mutualistic symbiotic relationship with a group of soil microflora. The BNF that occurs in bacteroids, as well as the ammonium assimilation into amino acids and ureides that occur in the plant cell fraction of nodules, requires a large amount of P in energy transfer during nodule functioning. Deficiency of P in soil at this crucial stage directly affects root growth, photosynthesis, sugar translocation, and many more functions which in turn directly or indirectly disturb N-fixation. So, therefore, P supplement and rhizobium inoculation is an important practice to enhance the soil N-fixation by increasing nodulation in legumes. But the mineral P sources are nonrenewable, and high-grade rock phosphates are expected to be depleted shortly. As the mineral P sources are nonrenewable, and solubility of P in soil is low and only 15–30% of applied fertilizer P is taken up by crops in the 1styear of its application. The efficiency of P fertilizer requires enhanced acquisition by plants from the soil which can be achieved by growing some legumes which are capable to grown in P deficient soils. Hence, developments of some adaptive strategies which can help to conserve the supply of P under the deficient condition and enhance fixation of N in legumes are needed for better productivity. Now a days, the molecular mechanism including maintenance of the P-homeostasis in nodules for rhizobia–legume symbiosis emerging as a main adaptive strategy to enhance P utilization in P-deficient soils.

15.11 Future Prospects

Worldwide production of grain legumes is increasing significantly due to their vast use in different situations including human food, animal feed, as well as industrial demands. Considering the increasing needs for human consumption of plant products and the economic constraints of applying fertilizer, there is a greater role for grain legumes in cropping systems, especially in regions where affordability of fertilizer is in question. Furthermore, in continuous removal of N by cereal monocropping systems, the capacity of the soil to supply sufficient quantities of N required for optimum yield is declining rapidly. Application of costly nitrogenous fertilizers continuously cannot subside the effect alone. So, therefore, N fertilizer must be supplemented with rotations utilizing legumes break crops which can increase supply and availability of N. BNF by various varieties or cultivars of grain legumes have become one of the most attractive strategies for the development of sustainable agricultural systems. Nevertheless, grain legumes have the ability to enhance the levels of SOM in cropping systems. Legumes can also play an important role in enhancing soil C sequestration. Besides N-fixation and high protein feed, legumes can also have considerable additional benefits such as positive impacts on biodiversity and soil quality. There is a great need for a strong focus on developing the role of legumes and their contribution to both a sustainable intensification of production and the livelihoods of smallholder farmers in many parts of the world.

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