Nitrogen and Phosphorus Use Efficiency in Agroecosystems

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Abstract

Nitrogen (N) and phosphorus (P) are two significant macronutrients for the growth and development of the plant. These two nutrients represent the highest percentage of fertilizer manufacturing and consumption in the agriculture sector. Though applied in versatility, N and P are subjected to huge losses in terms of fixation, leaching and volatilization. Nitrogen and P fertilizers have a net efficiency of 30–35%, and 18–20%, respectively. To cope with this issue, many advances have been made in terms of N sources and application methods. From split application to coating, and using nitrification inhibitors to minimize its losses, a wide range of techniques are reported. Application of organic amendments also contributes to net stabilization of N in the soil for a longer period. For coping with P losses, phosphatic fertilizers having an acidic residual effect is preferred in alkaline soil, along with indigenous P solubilization, slow-release P fertilizer modulation and use of coated fertilizers are some prominent options. Use of plant growth-promoting rhizobacteria (PGPR) to ensure sustainable N and P availability, uptake and utilization in crop plants are being advocated in this context. This chapter is an effort to comprehensively explain sources and fates of N and P in soil with special emphasis on modern ways and techniques for better management of these resources in agriculture.

Keywords

Agroecosystem · Fixation · Nitrogen · Nitrogen use efficiency · Phosphorus

Abbreviations

μg	Microgram
Al	Aluminium
AMF	Arbuscular mycorrhizal fungi
BNF	Biological nitrogen fixation
Ca	Calcium
CDU	Crotonylidene di-urea
cm	Centimetre
DAP	Diammonium phosphate
DPR	Dolomite phosphate rock
FC	Filter cake coated MAP
Fe	Iron
FYM	Farmyard manure
g	Gram
ha	Hectare
IBDU	Isobutylidene di-urea
kg	Kilograms
MAP	Monoammonium phosphate
Mg	Magnesium
MMT	Million metric tons
MPP	Monopotassium phosphate
Mt	Metric tons
N	Nitrogen
N_2O	Nitrous oxide
NBP	Nitrogen broadcast application
NBPT	N-(n-butyl) thiophosphoric triamide
NDP	Nitrogen deep placement
NH_3	Ammonia
NH_4^+	Ammonium
NO_3^-	Nitrate
NPK	Nitrogen, phosphorus, potassium
NRE	Nitrogen recovery efficiency
NUE	Nitrogen use efficiency
P	Phosphorus
PCU	Polymer-coated urea
PGPR	Plant growth-promoting rhizobacteria
PM	Poultry manure
POL	Polymer-coated MAP
PUE	Phosphorus use efficiency
RP	Rock phosphate
RZF	Root zone fertilization
SC	Compost coated MAP
SCU	Sulphur coated urea

SRF	Slow-release fertilizers
Tg	Tera-grams
TSP	Triple superphosphate
UF	Urea-formaldehyde
WSF	Water soluble fertilizers

7.1 Introduction

Sustainable food production that can meet the demand of the growing population is one of the biggest challenges of the twenty-first century (Tilman et al. 2002). A wide range of nutrients is being sufficiently applied into agroecosystem around the globe out of which phosphorus (P) and nitrogen (N) are of esteem importance. Both nutrients are a structural and integral part of the plant and human body making them the inevitable ones which must be applied exogenously in agriculture fields to get sustainable yield. Nitrogen in its available forms can be up taken from the soil and assimilated into plant body via various mechanisms (Vidal et al. 2014; Waqar et al. 2014) and can act as limiting nutrient for plants (Glass 2003; Waqar et al. 2014). Regardless of extreme importance and extensive application of N fertilizers in the agriculture sector, nitrogen use efficiency (NUE) is of major concern as it ranks in-between 30 and 35% around the globe because of the great variability in NUE determining parameters; efficiency of plants to utilize N, the efficiency of plants to uptake N and N harvest index (Ciampitti and Vyn 2013; Meena et al. 2018, 2020; Kakraliya et al. 2017). Over the last 50 years, an increase in the crop yields is less than threefolds, while the fertilizer application has increased tenfolds (Tilman et al. 2002; Verzeaux et al. 2017). This shows a considerable decrease in NUE over the period. The uncontrolled, non-stoichiometric and irregular application of N fertilizers without considering soil pool chemistry and plant needs lead to major flaws in NUE (Fageria and Baligar 2005). Extensive and uncontrolled application of N fertilizers is not only an economically unfit practice but also can leave long-lasting effects on the biosphere with the ultimate effects on humans (Hirel et al. 2007: Waqar et al. 2014). Nitrogen fertilizer application following other nutrients is the need of the hour to maintain a consistent and sustainable supply of N for sustainable agriculture production worldwide (Robertson and Groffman 2009). To reduce the losses of N, slow or controlled-release fertilizers are considered as a promising tool (Bedmar et al. 2005). Slow-release fertilizers (SRF) release N for several weeks, unlike the conventional fertilizers. Several products consist of low water-soluble compounds, urease and nitrification inhibitors which release N slowly after microbial or chemical decomposition. Tian et al. (2016) reported that the use of controlled-release fertilizer (CRF) increased the NUE (13.66%) and yield of rapeseed (*Brassica napus* L.) (12.37%) as compared to conventional fertilizer. Similarly, reduction in the emission of nitrous oxide (N_2O) by the use of urea-dicyandiamide was explained by Akiyama et al. (2015). However, organic amendments application such as poultry manure (PM), crop residues, farmyard manure (FYM), etc. significantly improve the soil fertility and health. It was also reported that organic amendments release nutrients more slowly as compared to inorganic fertilizers (Al-Gaadi et al. 2019). It was reported that 240 μg N g^{-1} (μg—microgram; g—gram) of soil was released in clover amended soil followed by 76–100 μg N g^{-1} of soil in manure and compost amended soil during a 97 days incubation experiment (Masunga et al. 2016). Apart from different fertilizer amendments, biological nitrogen fixation (BNF) is correspondingly very helpful in enhancing NUE and crop N demands. The BNF is a process in which microorganisms of different species use enzymes such as nitrogenase and convert the unavailable atmospheric N_2 to the plant-available forms (Varley et al. 2015). The exponential increase in NUE was reported with an increase in BNF (Islam and Adjesiwor 2017). The BNF of about 465, 452 and 102 kg (kilograms) N ha^{-1} $year^{-1}$ was reported by alfalfa (*Medicago sativa* L.), red clover (*Trifolium pratense* L.) and white clover (*Trifolium repens* L.), respectively (Islam and Adjesiwor 2017).

After N, P is an essential nutrient needed for proper growth of the plants and is subjected to a wide range of issues in agroecosystem from its rock reserves limitation to its least availability and higher fixation in soil (Hammond et al. 2009; Hasan et al. 2016). Due to the wide range of environmental constraints, current phosphorus use efficiency (PUE) rarely exceeds 25% and mainly falls in-between 18 and 20% worldwide (Syers et al. 2008; Mitran et al. 2018). The limiting constraints derived pressure become worse when a consistent supply of P to plants become inevitable for plant growth and sustainable yield production. Global P reserves are shrinking at a very fast rate with little-to-no renewability thus making smart use of P reserves inevitable (Roberts and Johnston 2015). At the current rate of consumption, rock phosphate (RP) reserves can be depleted within two to four centuries depending upon the cost, demand–supply relation, exploration of the reserves, future technological development and other factors (Kauwenbergh and Hellums 1995; Scholz and Wellmer 2013). The only way for increasing the life of current P reserves is the smart use of P fertilizers. It was reported that the use of SRF of P (Struvite) significantly enhanced the PUE as compared to conventional P fertilizers (Talboys et al. 2016). Several coating materials such as oil, polyethylene, latex, sulphur, polyvinyl chloride and other chemically synthesized compounds have been used to formulate SRF fertilizers (Xiang et al. 2008). Teixeira et al. (2016) used the organic acid-coated SRF of P. Results showed a significant recovery of P (+41%) by maize (*Zea mays* L.) as compared to conventional fertilizer. The addition of organic amendments enhanced the P nutrition and use efficiency. Luo et al. (2018) reported about 48% P acquisition by wheat crop (*Triticum aestivum* L.) from the soil with organic amendments. In the case of phosphatic fertilizers method of application significantly influenced the P use efficiency and the P availability to the crops. Applied P showed higher fixation and precipitation problems in the soil. A significant increase in wheat crop yield was recorded by side dressing of P fertilizer compared to the conventional broadcast method (Ali et al. 2012).

Use of biofertilizer or the microbial inoculants is also an important strategy to enhance the nutrient use efficiency. Many of the microbial inoculants can also act as biofertilizers because they can make nutrients accessible such as P and N from soil unavailable pools, from organic amendments, they can also fix N, improve the drought and salt tolerance of crops, improve the health of plants by reducing the disease incidence (Arora et al. 2013). Potential of arbuscular mycorrhizal fungi (AMF) and PGPR as biofertilizer is a well reported (Berruti et al. 2016; Rubin et al. 2017).

A small increase in P and N use efficiency can lead to long-lasting, huge economic and environmental benefits worldwide. Aiming to the great need of N and P in crop production with enormous application rate and various drawbacks in current application techniques leading to their wastage. The current chapter is an effort to summarize sources, fate and provide an overview of potential ways to enhance N and P use efficacies and increase their availability for agroecosystems.

7.2 Sources and Fate of Nitrogen and Phosphorus in the Environment

Application of N and P fertilizer was one of the major contributors to the green revolution aiming to produce enough food to feed the world. Among sources of N, plant and animal residues (Neff et al. 2002) and synthetically produced nitrogenous fertilizers using atmospheric N and natural gas (Mackenzie 1998; Galloway et al. 2013) are important. Nitrogen being an integral part of plant and animal bodies can make its way back in the form of plant residues and animal remains into the soil. Phosphorus in the soil is also present as organic and inorganic forms (Tomar 2003; Rosling et al. 2016). Organic forms of N and P does not contribute to the plant-available pool unless it gets decomposed and changed to inorganic ionic forms which can be taken up by crop plants. Inorganic forms of N and P readily available but are subjected to various constraints leading to their wastages like N leaching, fixation and volatilization, and P fixation in soil.

7.2.1 Nitrogen

The atmosphere contains about 79% of N, which is not available to plants as plants only uptake N when it is in nitrate (NO_3^-) or ammonium (NH_4^+) forms (Näsholm et al. 2009). Nitrogen added to the soil through several sources like fertilizers, crop residues, animal manures, natural fixation of N and sewage sludge is ultimately changed to mineral constituents and taken up by plants. Nitrogen mineralization, nitrification, denitrification and fixation are important domains of N cycle controlling its availability in soil (Ghaly and Ramakrishnan 2015).

7.2.1.1 Natural Sources of Nitrogen

Atmospheric N_2 needs to be converted into plant-available forms *via* breaking the strong triple bond ($N{\equiv}N$) requiring a lot of energy (Schlögl 2008) which can be provided by industrial and biological N fixation (Robertson and Groffman 2007). Though industrial N fixation seems major contributor, biological N fixation is more important as it is economical and independently occurring in agroecosystem resulting into the fixation of 200 million tons N year^{-1} into agricultural soils (Rascio and La Rocca 2008). In biological N fixation, free-living and symbiotic bacteria use nitrogenase enzyme responsible for the conversion of elemental N into mineral (NH_4^+) form (Postgate 1998; Mosberger and Lazzaro 2008). Various microbial species present in the soil contribute to N fixation in huge amounts, out of which some lives freely, and some make relations with plants called symbiotic association. Free-living N fixing bacteria contribute to 10–320 tons N ha^{-1} (Hectare) annually while bacteria in association with plant species (symbiosis) are responsible for 13–300 tons of N fixed per ha of soil annually (Bohlool et al. 1992).

Besides biological fixation, atmospheric N may enter soil N cycle through dry and wet atmospheric deposition in organic (urea, amines protein and nucleic acid) or inorganic forms i.e. ammonia (NH_3), NH_4, nitric oxide (NO), N_2O, nitric acid (HNO_3) and NO_3. Dry deposition is mainly caused by diffusion and wet deposition mainly happens by in-cloud developments and scavenging of below-cloud (He et al. 2010). Wet and dry atmospheric deposition contributes 11% of global N input (Whelan et al. 2013a, b). Application of organic amendments is also responsible for N contribution into the soil via mineralization process in which the most important thing is C:N ratio (carbon: nitrogen) of the amendment (Cherr et al. 2006; Fließbach et al. 2007; Whelan et al. 2013a, b).

7.2.1.2 Synthetically Produced Nitrogenous Fertilizers

Mineral fertilizers are a chief source of N for plant growth in current exhaustive agricultural practices in which soil indigenous N fixing capacity cannot surpass N losses from the soil. A wide range of nitrogenous fertilizers are available to be used including anhydrous ammonia (NH_3), ammonium sulphate [$(NH_4)_2SO_4$], calcium ammonium nitrate [$Ca(NO_3)_2\ NH_4{\cdot}NO_3$], and mixed N-P fertilizers such as di-ammonium phosphate [$(NH_4)_2HPO_4$] and monoammonium phosphate ($NH_4H_2PO_4$) (Whalen and Sampedro 2010). Industrially derived N fertilizers always use the basic mechanism of the Haber–Bosch process which involve the conversion of molecular N into NH_4 forms (Vojvodic et al. 2014). In the time of utmost need, inorganic N fertilizers act as quick supplementation when applied in agricultural fields at agronomic rates generally less than 200 kg N ha^{-1} (Fließbach et al. 2007). The fate of N in soil upon application as mineral fertilizer is mainly dependent upon the composition of fertilizer and soil conditions (Minet et al. 2012). Nitrogen fixation, nitrification, denitrification, leaching and volatilization are major possible fates of N in soil upon application primarily depending upon fertilizer composition and indigenous physicochemical properties of soil (Ghaly and Ramakrishnan 2015).

7.2.2 Phosphorus

Phosphorus is frequently available in the environment even it is not in the top 10 elements of hydrosphere or lithosphere. In the lithosphere, it is placed at 11th position having concentration 90–200 × 10^3 MMT (Million Metric Tons) P. In the hydrosphere, it has 13th position with a rough estimation of the P reserves of 80–120 × 10^3 MMT (Liu and Chen 2008). In the lithosphere, rock reserves of P are a major source of extractable P but have very less solubility and poor availability if applied untreated into the soil. The calcium phosphate apatite ($Ca_{10}PO_46X_2$), where X may indicate F (fluoride), OH (hydroxide) or Cl (chloride), fluorapatite, hydroxyapatite and chlorapatite contribute 95% for the total P of the lithosphere (Stumm 1977; Fleet et al. 2011; Korzeniowska et al. 2013). Another source of P in agroecosystem is an organic form consisting of plant and animal remains. Application of P into the soil is often accompanied by its fixation, precipitation, running off with water and immobilization making its recovery 10–30% (Brady and Weil 1999; Chien et al. 2011).

7.2.2.1 Natural Sources of Phosphorus

Out on the earth, millions of tons of phosphate reserves are presently being cited at oceans (93,000 Mt (metric tons) P), Soil (40–50 Mt P), Phytomass (570–625 Mt P) Zoomass (30–50 Mt P) and Anthropomass (30–50 Mt P) (Smil 2000). Hydrosphere P reserves are higher than that of the lithosphere, while volcanic and metamorphic contain short reserves of P element. Lithosphere P reserves although enormous (Soil 40–50 Mt P) are entirely plant unavailable (Smil 1999; Kesler et al. 2015). Since mid of the nineteenth century, we have been extracting most accessible and wealthy source of phosphate rock for industrial use and production of fertilizer to meet the crop requirements. According to an estimate in the top layer of soil (50 cm—centimetre), average P is only 0.05% (Stevenson and Cole 1999) and yields about 50 gigatons (Gt) P, or unevenly 3.75 tons P ha^{-1}. Organically fixed P (in phytates and nucleic acids) contribute up to 20–80% (Tomar 2003) of element existing in the soil and its existence naturally positively correlate with soil organic N.

7.2.2.2 Synthetic Sources of Phosphorus

There is no synthetic way to produce P without using natural mineral reserves. Conversion of natural reserves into more applicable plant fertilizer is observed in industrial manipulation of P. The current fertilizer industry initiated P compound production depends upon Liebig's law that P solubility in water will increase if bones were treated with sulphuric acid (Brock et al. 2007). Major synthetically produced phosphatic fertilizers are Monocalcium phosphate (MCP), Dicalcium phosphate (DCP), Diammonium phosphate (DAP), Monoammonium phosphate (MAP), Triple superphosphate (TSP), and Monopotassium phosphate (MPP) (Smil 2000).

Worldwide, out of total phosphate reserves, 95% are present in only 12 countries out of which America contributes 33% and China + Morocco own 66% of natural reserves while remaining 27 countries control the rest of it. There is a lot of discussion going on regarding average richness of already available RP in terms of their use as phosphatic fertilizer as only 2% or even less is being used in acidic soils directly as P fertilizer (Van Kauwenbergh 1995). For its conversion to more suitable fertilizer P, its industrial manipulation and treatments are done in almost every major P fertilizer producing country.

7.3 Concerns with Nitrogen and Phosphorus in Agriculture

Improper, unguided and unbalanced utilization of nitrogenous and phosphatic fertilizers have raised a huge concern regarding their contribution to environmental pollution. Nitrogen cycle involves the process of N transformation in the environment as NH_4-fixation, NH_3-volatilization, NO_3-leaching, runoff, denitrification, microbial mediated mineralization and fixation. Similarly, with phosphatic fertilizers, major fates are P fixation and runoff with later responsible for the process of eutrophication. Nitrogen leaching in well-irrigated lands has shown deep concerns regarding NO_3 pollution in surface and groundwater (Oenema et al. 2005), and nitrous oxide contributes to global warming (Reay et al. 2012) having the 300 times more potent than carbon dioxide (Robertson and Groffman 2009).

Phosphorus is quite different from that of the N. The long-term addition of P in agricultural lands and its loss to water bodies by runoff hasten the eutrophication and reduce crop uptake (Sharpley et al. 1995; Yang et al. 2008). Therefore, the management of P loss to water bodies must be a priority. Uptake of P by plants from chemical fertilizers and soil may be influenced by many environmental and soil factors i.e., the temperature of the soil and environment, soil compaction, moisture, aeration, pH, percentage texture, P status and other nutrients status in the soil (Munson and Murphy 1986; Hasan et al. 2016).

7.3.1 Nitrogen Gains and Losses in the Environment

Nitrogen is a complex and important element likewise carbon and oxygen in the plant and soil system. Use of N fertilizer has increased from the last 50 years and has contributed significantly to the up-gradation of the cereal production up to 40% per capita (Mosier et al. 2001). According to an estimate, synthetic N supplies around 40% of the dietary protein of the world and dependency on N fertilizer through the Haber–Bosch process will rise in the coming decades (Smil 2004). Some fates of N in the soil–plant system when it undergoes different processes are nitrous oxide formation, nitrification, leaching of NO_3 to groundwater, denitrification and volatilization in the form of NH_3 (Fig. 7.1). Nitrogen is broadly known as responsible for hypoxia (low oxygen) that changing the bio network and production of the bottom waters in a large area. In the environment, N can be removed from soil through the water and wind erosion. By water and wind erosion the top fertile layer of the soil removes and causes a reduction in soil fertility (Fageria 2002).

Leaching of inorganic N pool as NO_3 with water is a common problem in sandy type of soil and varies with climatic conditions; leaching losses in arid, semi-arid areas are negligible (Wang et al. 2014). Under extreme deficient conditions, N deficiency in agriculture soils can lead to stunted growth and decrease the productivity of crop plants (Zhu et al. 2019). Nitrogen fertilizer application method is another contributor in managing N losses in agricultural soils.

Methods like broadcasting, leave more N prone to atmospheric factors increasing chances of losses as volatilization (contributing up to 20%losses in alkaline soils),

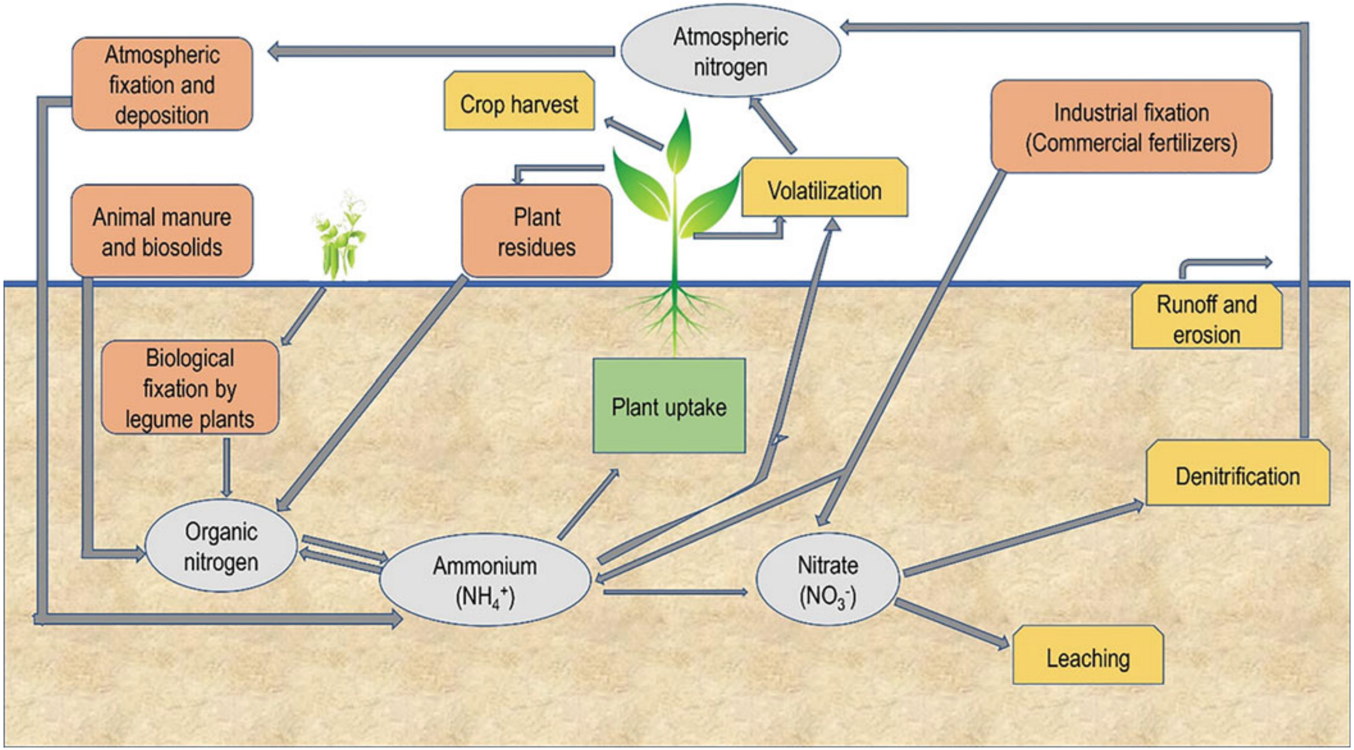

Fig. 7.1 Major nitrogen flows and stocks in agroecosystem (Source: Authors)

fixation and leaching (Fageria 2002). Soil physicochemical properties, fertilizer application methods and improper irrigation scheduling can contribute to N losses ultimately affecting plant physiology and biochemical machinery (Xu et al. 2012: Li et al. 2013).

7.3.1.1 Leaching

Aiming high solubility and mobility of NO_3^- in alkaline soil, N movement is more via mass flow thus increasing chances of losses via leaching (Jury and Nielsen 1989) degree of which is controlled by irrigation water source and availability (Meisinger and Delgado 2002). Nitrate leaching losses are more in coarse-textured soils receiving enough water necessary for net inflow/ percolation of water into the soil profile. Leaching losses of N are less in semi-arid to arid areas where net water movement is upward in the soil profile (Wang et al. 2014).

7.3.1.2 Volatilization

One of the many causes of low NUE in agroecosystems is the N volatilization in the NH_3 form. Nitrogenous fertilizers of NH_3-based composition are more prone to NH_3 volatilization if applied irregularly (Dominghetti et al. 2016; Pan et al. 2016). The leading concern for decades in agriculture is to improve the NUE of applied nitrogenous fertilizers (Chien et al. 2009). Vindicating NH_3 volatilization is immediately needed, a quantitative synthesis is lacking to assess the usefulness of mitigation strategies for NH_3 volatilization from synthetic fertilizers applied in agricultural systems (Pan et al. 2016). Smart formulation of N fertilizers having a balanced composition of NO_3 and NH_3 can be a suitable option if opted along with modern modifications to ensure long persistence of N in soil (Fan and Li 2010; Trenkel 2010). Though N volatilization is a significant cause of N loss, very little countries are working to solve this problem (Behera et al. 2013). Improper and unchecked addition of nitrogenous sources is a major cause for increased volatilization losses (Black et al. 1985; Turner et al. 2012; Bosch-Serra et al. 2014) which we can make 47–90% lower by adopting smart agriculture practices (Holcomb et al. 2011; Zaman et al. 2013; He et al. 2014).

7.3.2 Phosphorus Gains and Losses in the Environment

Various natural sources of P are present in the biosphere contributing to fulfilling P requirement for plants. In lithosphere, the soil is the most abundant and most related source of plant available P but it is subjected to various losses (Liu and Chen 2008; Liu et al. 2017) (Fig. 7.2). Some constraints regarding P availability in the soil are discussed below.

7.3.2.1 Fixation

Phosphorus fixation in agricultural soils is a well-known and established fact with various factors responsible for its (Kanwar and Grewal 1990) decreasing availability of P from exogenously applied fertilizers (Chien et al. 2012). Both chemical and

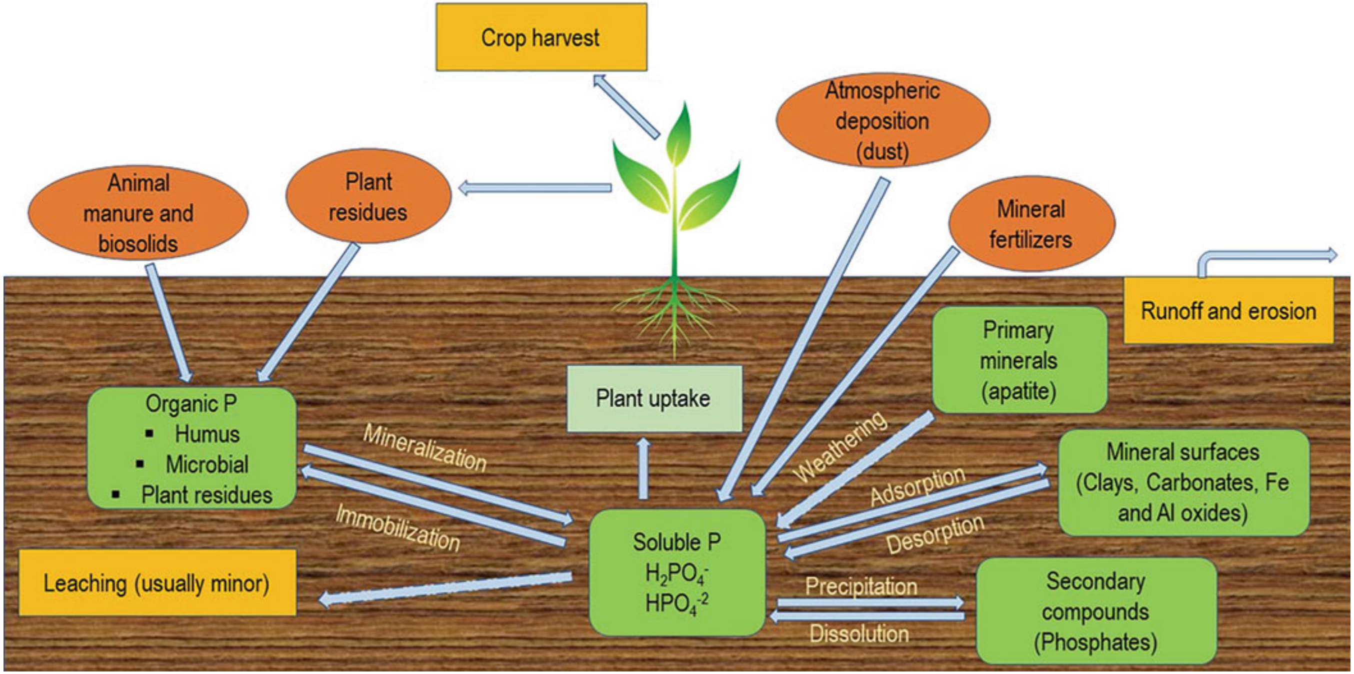

Fig. 7.2 Phosphorus gains and losses in the soil–plant system

biological (into the microbial body) fixation of P in the soil are present but chemical fixation is a dominant phenomenon. In acidic soils, P gets fixed with iron (Fe) and aluminium (Al) ions (Gerke 1992), while in alkaline calcareous soils, calcium (Ca) is the dominant cation for phosphatic precipitation (Kanwar and Grewal 1990). The labile pool of P experiences two kinds of the phenomenon on exchange sites; adsorption and desorption responsible for homeostasis of ionic phosphate in soil solution.

7.3.2.2 Adsorption-Desorption

Regarding P availability in soil, adsorption–desorption phenomenon is also quite significant in which phosphate ions are detained on exchange sites of soil (Khan et al. 2010) and/or on Al & Fe minerals (Wang et al. 2013a, b). Soil solution and exchange sites adsorption-desorption of P is of great concern regarding the maintenance of P balance in the rhizosphere (Hongshao and Stanforth 2001; Kim et al. 2002).

7.4 Enhancing Nitrogen Use Efficiency for Sustainable Agriculture

In the past few decades malpractices regarding agrochemicals have given an immense push to soil degradation (Galloway et al. 2004) and excessive N flush from agroecosystem can lead it directly to the human food chain (Robertson and Groffman 2009). Loss of N fertilizer depends on agroecosystems, characteristics of soil, application method and chemical form of fertilizer (Chen et al. 2008). The only way of decreasing nitrogenous fertilizer losses is to increase its use efficiency via adopting several modern and precision agriculture based techniques involving the use of more persistent forms and modifications in application methods.

7.4.1 Innovations in Nitrogen Sources

Nitrogenous fertilizers are highly water-soluble, and this property of N fertilizers leads to the loss of N from agricultural systems. Different physical and chemical methods can be used to reduce the solubility of N fertilizers, i.e. coating or encapsulation and the conversion of N to polymeric less soluble forms (Tables 7.1 and 7.2).

7.4.1.1 Condensation Polymers

Condensation polymers include isobutylidene di-urea (IBDU), urea-formaldehyde (UF) and crotonylidene di-urea (CDU). Urea-formaldehyde is one of the oldest slow-release N fertilizers. Urea-formaldehyde fertilizer can be produced in different forms like solid granules, suspensions, powders and liquids. Many agronomic studies provided evidence of the slow release of N from UF and UF-modified fertilizers.

Nardi et al. (2018) conducted a study to evaluate the release of N from slow-release fertilizers (SRF). Three SRF were added into the soil including CDU, UF and

Table 7.1 Effect of different nitrogen and phosphorus fertilizers and application methods on crop yields

Fertilizer type	Formulation	Application method	Increase in yield	Reference
Nitrogen	Urea	4 split application	57.8%	Belete et al. (2018a, b)
	Urea super granules (USG)	Deep placement	1.66 t ha^{-1}	Xiang et al. (2013)
	Urea	Urea deep placement (UDP)	10%	Yao et al. (2018)
	Urea-ammonium nitrate	Point-injected	0.66 t ha^{-1}	Stevens et al. (2007)
	Urea	RZF	11.5%	Jiang et al. (2018)
	Calcium nitrate [$Ca(NO_3)_2$]	Drip fertigated	1 t ha^{-1}	Danso et al. (2015)
	Urea	RZF	4.3–44.9%	Liu et al. (2016)
	Single superphosphate (SSP)	Broadcast	0.55 t ha^{-1}	Arif et al. (2010)
	Polymer-coated urea (PCU) broadcast	Subsurface band	39 kg ha^{-1}	Barker and Sawyer (2005)
	Urea	Soil application	2.14 t ha^{-1}	Alam et al. (2010)
	Urea	LN^{-1} topdressing (distances 15 cm)	3.87 t ha^{-1}	Yong et al. (2018)
	Urea	Fertilization banding placement in one side of seedling (FBPOSS)	46.15%	Bakhtiari (2014)
Phosphorus	P_2O_5	Intra-row drilling	2.03 %	Ali et al. (2004)
	Liquid (nitrophos)	Fertigation	28.95%	Alam et al. (2003)
	Polymer-coated MAP (POL)	–	3.48 t ha^{-1}	de Figueiredo et al. (2012)
	Glycerin + polymer-coated DAP	Three equal splits	3.04 t ha^{-1}	Imran et al. (2018)
	Granules (DAP)	Side dressing	49.43%	Rahim et al. (2007)

(continued)

Table 7.1 (continued)

Fertilizer type	Formulation	Application method	Increase in yield	Reference
	Controlled-release phosphorus pentoxide (P_2O_5)	Applied basal dosage	12.37%	Tian et al. (2016)
	Granules (SSP)	Fertigation	11%	Iqbal et al. (2013)
	Orthophosphoric acid (OP)	Fertigation	28%	Badr et al. (2015)
	Water-soluble monoammonium phosphate	Fertigation four times	14.17%	Li et al. (2019)
	Triple superphosphate	Foliar application	0.69 t ha^{-1}	Mosali (2004)

IBDU and treatment includes simple urea. Results indicated that N release from different fertilizers was as: UF (46–73%), urea (89–100%), CDU (44–56%) and IBDU (59–94%), respectively. Xiang et al. (2018) formulated an SRF (GSRFEx) using ammonium polyphosphate (APP), UF and amorphous silica gel (ASG) and experimented on rape crop (*Brassica* spp.). Results showed that GSRFEx is a better source to improve NUE dramatically. The efficient slow release of N was also reported by a fertilizer developed using UF nanocomposites by Yamamoto et al. (2016).

7.4.1.2 Coated Fertilizers

Coated fertilizers are made via physical or chemical coating of nitrogenous fertilizer with any desired material. In coated fertilizers, nutrient release depends on the properties of coating material, coating thickness and integrity of coating (Varadachari and Goertz 2010). Different materials like sulphur, polymers, neem oil, resins and gels, clays have been used for the coating of urea fertilizer (Tables 7.1 and 7.2).

Tong et al. (2018) experimented the evaluation of controlled release of urea on the dynamics of NO_3 and NH_4. Polyurethane coated urea and sulphur coated urea (SCU) were used. Results indicated that SCU reduced the concentration of NO_3 and NH_4, while the PCU was even more efficient than SCU. Increased nitrogen recovery efficiency (NRE) up to 60% was reported by SCU (Shivay et al. 2016). Halvorson et al. (2014) reported that nitrous oxide emission is reduced up to 42% by urea coated with polymer compared to conventional urea fertilizer. Wang et al. (2015) developed a novel polymer from recycled plastics and coated urea with that polymer at the rate of 6, 8 and 12%. Results indicated that coated urea fertilizer better met the plant N demands, reduce the volatilization and increased ^{15}N recovery. Bortoletto-Santos et al. (2020) have reported most recent accepted work in which they used coated urea using polyurethane derived from castor (*Ricinus communis*) and soybean (*Glycine max*) oil and results showed that release of urea could be controlled by varying

Table 7.2 Effect of different nitrogenous and phosphatic fertilizers on yield of different crops (% difference compared to control)

Crop	Variety	Rate of fertilizer	Type of fertilizer	% grain yield increase (%)	Reference
Wheat	Menze	360 kg ha^{-1}	Urea	302.55	Belete et al. (2018a, b)
	Ujala-2016	145 kg N ha^{-1}	Urea	196.30	Ullah et al. (2018)
	Winter wheat	150 kg N ha^{-1}	Coated urea	32.72	Fan et al. (2004)
	Yangmai 20	225 kg N ha^{-1}	Urea	3.76	Zhang et al. (2017)
	Naseer 2000	90 kg ha^{-1}	P_2O_5	21.9	Khan et al. (2007)
	Inqulab-91	81 kg ha^{-1}	P_2O_5	149.36	Rahim et al. (2010)
	Yangmai 9	108 kg ha^{-1}	P_2O_5	31.8	Zhu et al. (2012)
	Atta Habib-2010	144 mM foliar	KH_2PO_4	35	Rafiullah and Muhammad (2017)
Rice	Proagro 6207	100 kg ha^{-1}	Super Net	36.8	Chaturvedi (2005)
	BRRI Dhan-29	50% app. of N Rec. Lvl.	Biofertilizer (BRRh-5)	100	Khan et al. (2017)
	Sakha 108	220 kg N ha^{-1}	Urea	102.52	Ghoneim et al. (2018)
	Not given	60 kg P ha^{-1}	Minjingu mazao (MM)	494.9 site 1 595.5 site 2	Massawe and Mrema (2017)
	IRRI-6	90 kg ha^{-1}	P_2O_5	75	Khan et al. (2007)
	BRRI Dhan-29	50% application of the recommended level of P	Biofertilizer (BRRh-5)	100	Khan et al. (2017)
	Weiyu 64, Hybrid 78130, Dingyu, Dofu, Hybrid 428, Eyou 938, Shuanyou 2292	104 kg N, 12 kg P, 113 kg K+ 3750 kg cattle manure	NPK fertilizer + cattle manure (NPKM)	97	Lan et al. (2012)
Maize	Rampur Composite	200 kg N ha^{-1}	Urea	154.74	Shrestha (2015)

(continued)

Table 7.2 (continued)

Crop	Variety	Rate of fertilizer	Type of fertilizer	% grain yield increase (%)	Reference
	ZM 621	180 kg N ha^{-1}	Urea	44.93	Pokhrel et al. 2009)
	DEKALB C60-19	168 kg N ha^{-1}	Anhydrous ammonia + polymer-coated urea (PCU)	23	Noellsch et al. (2009)
	Elite 20T06	150 kg N ha^{-1}	Polymer-coated urea (PCU)	108	Gagnon et al. (2012)
	Single Hybrid 10	476 kg ha^{-1} and 20 t ha^{-1}	Superphosphate + FYM	44.6	El-Eyuoon and Amin (2018)
	Not given	Desired 100 kg P ha^{-1}	50:50 PM or FYM+DAP	45.8	Ali et al. (2019)
	BH 660	18.3 kg P from Tithonia + 2 kg p from TSP ha^{-1}	10% P (TSP) + 90% P (Tithonia)	79	Endris (2019)

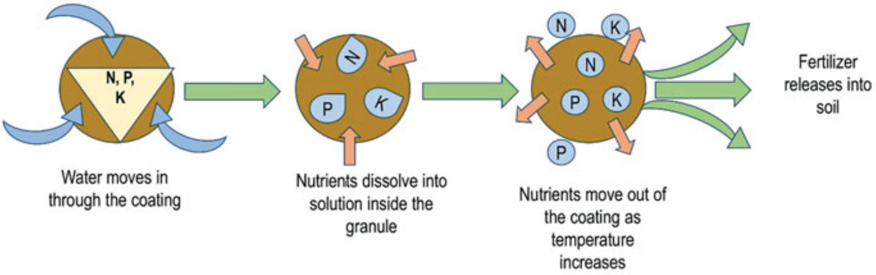

Fig. 7.3 General nutrient release mechanism of coated fertilizers

coating thickness and they also declare the better strategy to coat urea with the eco-friendly polymer. A general mechanism of the release of nutrients from a coated fertilizer is presented in Fig. 7.3.

Jadon et al. (2018) reported that NH_3 volatilization was reduced up to 27.5, and 41.1% by neem coated urea and pine oleoresin coated urea, respectively, and the leaching of NO_3-N is reduced up to 18.3, 28, 25.7 and 35.1% by neem coated, resin coated, nano-rock phosphate coated and ZnO nanoparticle (zinc oxide) coated urea, respectively.

7.4.2 Stabilized Nitrogen Products

7.4.2.1 Nitrification Inhibitors

Nitrification inhibitors have been used in agriculture to lower down the losses of N in gaseous form by slowing down the process of nitrification and to enhance the yield of the crops (Randall and Vetch 2003; Frame 2017; Ren et al. 2017). The slowdown of the nitrification process force N retention in the soil in the form of less mobile NH_4 form which ultimately reduced the leaching losses of NO_3-N (Rybárová et al. 2018).

Rybárová et al. (2018) conducted a study to evaluate the effectiveness of nitrification inhibitors in soil. In this study, a nitrogen-sulphur fertilizer ENSIN which also contains dicyandiamide and 1,2,4-triazole as nitrification inhibitors have been added. Soil analysis showed that application of ENSIN reduced the NO_3-N in soil up to 32% when added in a single dose, while the split application of ENSIN reduced NO_3-N up to 62%. Application of Dicyandiamide as a nitrification inhibitor significantly reduced nitrous oxide emissions up to 20% (Misselbrook et al. 2014). Lam et al. (2017) claimed that nitrification inhibitors reduced the direct nitrous oxide emissions up to 8–57%. Application of DCD at 5, 7 and 10 kg ha^{-1} reduced nitrous oxide emissions of 25, 47 and 47%, respectively (Zaman and Blennerhassett 2010). Very recently, Ashraf et al. (2019) reported decreased N losses via increased N recovery, improved growth and yield of maize due to applied organic materials (neem oil (*Azadirachta indica*), moringa leaf extract (*Moringa oleifera*), pomegranate extract (*Punica granatum*)) coated on urea as nitrification inhibitors.

7.4.2.2 Urease Inhibitors

One of the strategies to enhance NUE and to reduce the pollutants generated by urea hydrolysis is the use of urease inhibitors (Modolo et al. 2015; Li et al. 2017; Mira et al. 2017). Urease is an enzyme that converts urea into NH_3 and having wide distribution, it can be found in soil, plants and microbes, etc. (Follmer 2008).

Li et al. (2015) proved that application of N (propyl) thiophosphoric triamide (NPPT) along with urea reduced the NH_3 volatilization up to 50% compared to control treatment. According to (Ni et al. 2014) recently studied phosphoric triamide (2-NPT) and N-(2-nitrophenyl) as a urease inhibitor to reduce the NH_3 volatilization up to 26–83%. Cantarella et al. (2018) conducted a study using N-(n-butyl) thiophosphoric triamide (NBPT) as a urease inhibitor. Results showed that application of NBPT with urea reduced NH_3 volatilization up to 53%.

7.4.3 Innovations in Nitrogen Application Methods

Method of application of N fertilizer plays an important role in NUE (Zhu and Chen 2002; Wang et al. 2016). Inappropriate application method also leads to environmental problems like atmosphere contamination, degradation of soil quality and water pollution (Davidson 2009; Reay et al. 2012) (Table 7.1). Thus, efficient nutrient management techniques are needed to increase NUE, crop yield and to reduce environmental pollution (Guo et al. 2008; Chen et al. 2014). Efficient nutrient management techniques largely depend on application method, type of fertilizer and the rate of fertilizer addition (Cui et al. 2010; Nash et al. 2013; Zheng et al. 2017). Many researchers reported that splitting of N fertilizer dose enhances the NUE significantly and reduces the losses of N which ultimately increased the crop yield (Chen et al. 2011; Kettering et al. 2013). Wang et al. (2016) stated that recovery efficiency of N for three split and two split fertilizer application is much higher than the one-time application of whole fertilizer dose as basal dressing, this practice also reduces N losses remarkably. Recently, Yao et al. (2018) stated that N recovery efficiency has been improved up to 55%, and 91% decrease in NH_4 volatilization was recorded by deep placement at one point compared to surface split broadcasting. According to the studies conducted previously, agronomic fertilizer efficiency and crop yield by the deep placement of fertilizers are much higher compared to the conventional split application by farmers (Mohanty et al. 1998; Jiang et al. 2018). Wu et al. (2017) established a field and pot studies to access the effectiveness of nitrogen deep placement (NDP) over nitrogen broadcast application (NBP). Results indicated that NRE and grain yield of the crop were increased significantly by NDP compared to NBP. Pot experiment results showed that NDP could maintain higher N supply in 5–20 cm soil layer compared to NBP which enhances absorption of N in plants and ultimately leads to higher NRE.

It is reported that N fertilizer application in the root zone (root zone fertilization) proved a good application method to reduce N losses in rice (*Oryza sativa*) fields and wheat–soil system (Chen et al. 2016; Liu et al. 2016). Root zone fertilization (RZF) in summer maize 12 cm deep and 5 cm away from seed proved to be a good RZF method (Jiang et al. 2017). Jiang et al. (2018) experimented to evaluate the effectiveness of one-time RZF and the results showed that RZF enhanced the yield up to 7% and increased the ^{15}N recovery remarkably up to 28.7%. Reduction in N losses up to 30.2% was also recorded. According to Zenawi and Mizan (2019) placement of fertilizer 5–10 cm away and 3–5 cm deeper in soil from seed could be a better strategy.

Shrestha et al. (2018) explained that addition of N source as a basal dose and split application at critical growth stages like at knee height and flowering stage are necessary to enhance crop yield. Bakhtiari (2014) reported that band placement on one side of the seed of N fertilizer 5 cm deep and 10 cm away from seed was the best method for N application. Yong et al. (2018) also stated that NUE, N uptake and agronomic use efficiency of N significantly increased up to 12.4, 72.5 and 51.6%, respectively, by top dressing compared to the conventional application method.

7.4.4 Use of Amendments for Better Nitrogen Conservation

Organic amendments application to the soil to maintain fertility status and soil health is the soil management strategies (Killham 2011), including N which is one of the most important nutrients in low input managed farming systems. Manure, litter from animal farms, composts and green manure are considered as important soil amendments and once they mineralize than these are considered as major nutrient sources (Nin et al. 2016; Niamat et al. 2019). Soil organic matter and N are important components of soil fertility. Due to more effect on soil biological, chemical and physical properties green manure considered as a more important and effective amendment in soil fertility management by researchers, agronomists and governments globally. Nowadays we can find several opportunities to grow green manure crops on your farm like intercropping, crop rotation and cover crops (Power et al. 1986; Nin et al. 2016). Intercropping of green manures enhances NUE, increases weed control, reduce the N losses and ultimately increases the yield (Jensen et al. 2015). The additional benefit of green manure crops is that they can fix atmospheric N, which stores in organic N form and available when the residues decomposed completely (Hardy 1993). Green manures can produce biomass up to 5–9 tons ha^{-1} $year^{-1}$ which includes about 40% dry matter as carbon and about 2–4% as N (Nin et al. 2016). Different green manure crops have different N productivity like 80 kg for berseem clover to 190 kg sub clover ha^{-1} (Nin et al. 2016). Fowler et al. (2004) conducted a study to evaluate the effect of three green manure crops including oat (*Avena sativa*), lupin (*Lupinus* sp.) and oat-lupin mix on NO_3 leaching in winter and N uptake and yield of the following crop. Results indicated that winter NO_3 leaching was reduced significantly, and the N uptake and dry matter production of upcoming ryegrass crops was increased significantly. Islam et al. (2015) conducted research using different green manure crops and various N chemical fertilizers in rice. Results showed that crop growth parameters and N uptake and recovery have been increased significantly by green manure incorporated crops in rice.

Returning of crop straw after harvesting the crop to the soil is an economical, sustainable and promising approach to improve soil fertility and to sequester the carbon (Dikgwatlhe et al. 2014). Double rotation of summer maize and winter wheat is a common and intensive cropping system used in china mostly. In this system, the main focus is on the chemical fertilizers so in this condition, returning of crop stubbles to the soil is important to maintain soil fertility (Liu et al. 2014; Meena et al. 2020). Residues of the crop change the primary macro nutrient (NPK) turnover (Luxhoi et al. 2007; Damon et al. 2014). Maize crop residues act as an important component of soil N pool because they contain about 80 kg N ha^{-1} (Burgess et al. 2002), and one of the major sources of N for the upcoming crop on the farm (Álvarez et al. 2008; Akkal-corfini et al. 2010). Availability of N from crop residues in soil crop system is entirely different than chemical N fertilizers because in this case availability of N depends on the decomposition of residues (Douxchamps et al. 2011). Hu et al. (2015) applied ^{15}N labelled crop residues to soil and the results indicated that 8.4% of the N from residues was recovered in the first growing season and the major part of the remaining N (61.9–91.9%) was recovered in the upcoming seasons. The N concentration in the soil was increased up to 73.8% by sequential application of crop residues.

Animal farm manure, PM and compost products are also consisting of higher amounts of N and other nutrients as well which can reduce the demand of chemical fertilizers to maintain soil fertility (Darzi 2012). Apart from supplying nutrients like N organic manures also improve soil biological, chemical and physical properties

(Najm et al. 2012). Pitta et al. (2012) applied a different amount of PM to the soil. Results demonstrated that during the first 30 days the dry matter loss was highest and 40% of the N was released during the first 60 days. After completion of 1-year residual N of PM in soil was 27%. Yeshiwas et al. (2018) conducted a field experiment to evaluate the effectiveness of integrated use of FYM and chemical fertilizers. Amount of FYM was 0, 15 and 30 t ha^{-1} and levels of N were 0, 75 and 150 kg ha^{-1}. Results indicated that 30 t ha^{-1} FYM + 75 kg ha^{-1} N significantly increased the lettuce (*Lactuca sativa*) yield. Many scientists evaluated the effect of FYM alone and along with chemical N fertilizers and significant results of soil fertility enhancement and crop yield improvement were recorded (Shakoor et al. 2015). Addition of pig slurry composting to soil at 4, 8 and 12 Mg (Mega-gram) ha^{-1} significantly increased the growth and yield parameters of millet crop (*Pennisetum glaucum*) (da Silva Mazareli et al. 2016). Horrocks et al. (2016) added municipal compost which generally consists of 2–2.5% of N in the soil. Results demonstrated that about 13–23% of N released from compost was used by crops in 2–3 years. Niamat et al. (2019), in another study, reported increased contents and uptake of N and P in maize with the application of Ca-fortified animal manure.

7.4.5 Role of Symbiosis in Nitrogen Nutrition

Nitrogen fertilizers applied to the crops to increase food production so, in this situation, it is needed to adopt more sustainable approaches like sustainable intensification and climate-smart agriculture (Jangir et al. 2016; Meena et al. 2016). The process in which microorganisms fix atmospheric N_2 to plant-available forms using nitrogenase enzyme is called BNF (Unkovich et al. 2010; Varley et al. 2015). Before the industrial revolution, it was the main source of N to crops (Vitousek et al. 1621). Researchers agreed that BNF is the most sustainable approach and it is known that NUE is increased by increasing biologically fixed N in the soil while the application of chemical N fertilizers reduced NUE linearly (Lassaletta et al. 2014). Fixation of N which is carried out by association between seed and rhizobacteria and leguminous crops is considered as one of the major sources for the reduction of N in the agricultural system (Liu et al. 2011; Peix et al. 2015). According to the stats presented by Food and Agriculture Organisation (FAO) annual N fixation by oilseed crops were 18.5 Tg (Tera-grams) N and 2.95 Tg N by pulses (Herridge et al. 2008; Islam and Adjesiwor 2017). Contribution of biologically fixed N is 25 Tg N which is dominated by 100 Tg N by chemical fertilizers (Lassaletta et al. 2014). It is reported that nearly 80% of BNF resulted from plant–microbe (leguminous plants + *Rhizobia* sp.) symbiotic relationship (Vance 1998; Mabrouk et al. 2018). Symbiotic relation of plants with stress-tolerant rhizobia species can increase the N fixation by increasing nodulation under stressful environment (Zou et al. 1995; Mabrouk et al. 2018). Verzeaux et al. (2017) reported that conservation or no-till system increases the AMF association with plants compared to the conventional tillage system. According to studies it is reported that AMF plays an important role in the uptake of nutrients like N and P. Bücking and Kafle (2015) reported that N can be transported to the host plant by AMF. Nowadays the use of biofertilizers is increasing day by day. Biofertilizers is a material which consists of living microbes and can be applied to soil, seeds and plants and after that, those living microbes start growing in the root zone and inside of the plant body and improve plant health by increasing the nutrient supply and by suppressing diseases (Bardi and Malusà 2012; Malusá and Vassilev 2014; Ali et al. 2017). Biofertilizers play a major part in increasing fertility of the soil by fixing atmospheric N and by the production of plant growth-promoting materials (Mazid and Khan 2015). Plant growth-promoting bacteria include the microbial species which are free-living, endophytes (which colonize some plant tissues) and the species which make symbiotic associations with plants and cyanobacteria (Farrar et al. 2014).

7.5 Enhancing Phosphorus Use Efficiency for Sustainable Agriculture

7.5.1 Innovations in Phosphorus Sources

Fertilizer type is one of the main factors which influences the P availability and adsorption (Tables 7.1 and 7.2). Fertilizers which are more soluble release P in soil solution more rapidly compared to slow-released or less soluble fertilizers. Contact time of P to soil colloids directly influence the intensity of P adsorption to soil (Laboski and Lamb 2003; Stauffer et al. 2019). Currently, polymer-coated P fertilizers have been used to increase the period in which P is available to plants (Trenkel 2010). Polymer coatings on P fertilizers significantly slow down the release of P and to reduce the adsorption of P by minimizing the direct contact of fertilizers to the soil colloids (Stauffer et al. 2019). de Figueiredo et al. (2012) carried out an experiment to evaluate the effect of polymer-coated and uncoated P fertilizers on maize production and the results showed that polymer-coated fertilizers increased the maize production up to 3.48 t ha^{-1} compared to uncoated fertilizer. Imran et al. (2018) carried out a study to evaluate the effect of polymer-coated DAP, conventional DAP, glycerine coated DAP. Results indicated that polymer-coated DAP significantly increased the growth parameters and uptake of P in wheat. Similarly, Rosling et al. (2016) evaluated the performance of slow-release fertilizers by using commercial and polymer-coated MAP and DAP. Results of incubation study showed that uncoated fertilizers released the total P within 10 days of the application, while the coated P fertilizers released (MAP—77% and DAP—57%) of P in the first 45 days after application.

Another slow-release P fertilizer preparation technique is to mix the P fertilizer with organic manure (Table 7.1) or coating with an organic acid (de Castro et al. 2015). In this technique adsorption of P to soil colloids is reduced and the organic acids also protect the P in soil solution chemically by binding P around organic acid granules (Stauffer et al. 2019). It is also reported that organic acids bind with Al and Fe thus reducing P fixation to Al and Fe (Guppy et al. 2005). Stauffer et al. (2019)

conducted a study to evaluate the release of P from commercial, polymer-coated and organophosphate coated MAP. The commercial MAP, POL, filter cake coated MAP (FC) and swine compost coated MAP (SC) were used. Results showed that the release of P within 14 days of application compared to control was 54.9–54.2% SC, 83.2–84.4% FC, and 88.5–95.4% POL. So, it was estimated that coating of P fertilizers with organic materials can be a good technique to maintain the release of P with time. Teixeira et al. (2016) conducted a study using different organic acids coated MAP. They used Commercial MAP (MAP_1), MAP_2 = natural organic acid-coated, MAP_3 = synthetic organic acid-coated, MAP_4 = Peat humic organic acid-coated. Results indicated that maximum slow release was recorded with MAP_4. It was also noted that the agronomic efficiency of P is 11–13% higher in organic acid-coated fertilizers compared to commercial MAP.

Dolomite phosphate rock (DPR) containing P, Ca and magnesium (Mg) is also considered an important alternative P fertilizer in acidic sandy soils. An experiment is established by Yang et al. (2012) to evaluate the effectiveness of DPR in acidic sandy soils of Florida. They used DPR and other water-soluble fertilizers (WSF) in ryegrass (*Lolium*). It was evaluated that DPR proved to be superior compared to other WSF. DPR increased the growth and P uptake in ryegrass. It was also recorded that DPR can increase the pH of acidic soils.

It was reported that the use of P with urea can enhance P-fertilizer use efficiency (Giroto et al. 2017). Agreeing to Anstoetz et al. (2015), P fixation can be reduced by mixing phosphate with urea in a single matrix. Giroto et al. (2017) carried out a study to evaluate the availability of N and P by nanocomposite slow-release fertilizers. In this experiment, nanocomposites were produced using urea and then mixing of hydroxyapatite particles was done. Results showed that the interaction of hydroxyapatite with urea matrix released P slowly and reduced the adsorption on soil colloids.

Another natural clay mineral attapulgite is also known as palygorskite also used to coat micronutrient fertilizers. Attapulgite itself also used as a major source of micronutrient and other beneficial elements as it consists of Ca, Mg, Fe, K, manganese (Mn), Al and silicon (Si) (Xie et al. 2011a, b). Attapulgite shows some good properties like higher surface area, higher water retention capacity, high adsorption capacity and slow release of ions. Yang et al. (2010) reported that use of attapulgite along with other compound fertilizers increased the crop yields. According to Guan et al. (2014), attapulgite coated fertilizers showed slow-release behaviour and increased the crop yield by 15.1–18.4% compared to control treatment.

7.5.1.1 Application Methods of Phosphorus

There are two main categories of P application methods broadcasting and band placement (Noonari et al. 2016). Broadcast method is easy, economical and time-saving but only valuable when after broadcasting you have to cultivate the soil using cultivators of disk harrows. Broadcast method is a less efficient method of P application because in this method contact area of P fertilizer to soil colloids is greater which enhances the fixation of P to Al, Fe and Ca and reduce the availability to plants (Vance et al. 2003; Syers et al. 2008; McLaughlin et al. 2011). Phosphorus losses and environmental problems related to the placement of P fertilizers in the soil like runoff of P linked with the eutrophication of water bodies (Chien et al. 2009). But some scientists also reported that broadcast application of P to some crops is a better strategy rather than band placement. Ma et al. (2009) explained that as compared to broadcast, deep placement of P source reduce the yield of the crop and causes P deficiency at the seedling stage. Similarly, Hu (2016) stated that horizontal placement of P 12 cm away from rice seedlings cause a reduction in crop yield compared to the broadcasting of P fertilizer. Lu et al. (2018) evaluated the effectiveness of broadcast and band placement of P fertilizer. Results showed that band placement increased the yield of wheat as compared to broadcast application but the placing of P fertilizer 12 cm apart from seed reduce the P uptake and yield compared to a broadcast application.

Noonari et al. (2016) experimented to evaluate the response of two different P placement methods—drilling method and broadcast method. They concluded that drilling of P was a better method for increasing the uptake of P and the yield in comparison to conventional broadcast method. Ali et al. (2012) experimented by placing P fertilizer in different ways in wheat crop like broadcast (M1), side dressing (M2), broadcast at the time of sowing + before 1st irrigation (M3) and broadcast at 1st irrigation (M4). Results showed that side dressing of P at the time of sowing increased the fertile tillers, growth and grain yield as compared to other application methods. Duarte et al. (2019) concluded that localized application of P was a better strategy to apply P compared to a broadcast application. Tariq et al. (2012) also determined that the side dressing of P fertilizer is a better application method for increasing growth, yield and P uptake of plants.

Application of P using fertigation technique can also be a good strategy to increase crop growth and production compared to conventional application methods. Badr et al. (2015) led an experiment to evaluate the effectiveness of fertigation technique on eggplant (*Solanum melongena*). They applied P as a pre-plant application of superphosphate and fertigation of orthophosphoric acid. Results displayed that fertigation of P increased the growth of plants, increased the number of fruits and ultimately increased the overall yield of eggplants.

7.5.1.2 Use of Amendments for Better Phosphorus Conservation

Rock phosphate (RP) is the raw material used to prepare synthetic P fertilizers. Rock phosphate is a non-renewable material and it is assumed that existing reserves of RP can be depleted in 50–100 years (Cordell et al. 2009). Mainly in the agriculture sector, P application is based on mineral P fertilizers. We need to explore new fertilization strategies to maintain soil fertility and plant nutrition requirements and to produce enough food to fulfil the requirements of the growing population (Faucon et al. 2015). One of the solutions can be the recycling of P from organic wastes/products like biochar, sewage sludge, PM and crop residues (Ott and Rechberger 2012; Lwin et al. 2017). Biochar is produced by the pyrolysis of biomass material under low or no environmental oxygen (Lehmann and Joseph 2015; Placido et al. 2016). The application of biochar is reported to lower the precipitation of P with Fe and; therefore, enhanced the P availability (Cui et al. 2011). In this regard, the application of biochar at 1.0 t ha^{-1} along with mineral fertilizers gave better performance compared to mineral fertilizers alone, as concluded by Glaser et al. (2015). Recently Santos et al. (2019) used granulated biochar with TSP specified that dry matter production and P uptake was increased in maize. They also noticed the increased soil available P with this combination. Likewise, the application of compost and biochar made from pineapple waste increased the total P, available P, and their organic and inorganic fractions in the soil (Ch'ng et al. 2014). Kizito et al. (2019) added digestate enriched biochar to soil and reported that total P was increased up to 450% by corn biochar and 170% by wood biochar.

Organic wastes and sewage sludge include various forms of P including organic and inorganic fractions depending on the processes of treatments (Frossard et al. 1996). Mostly the dominant organic fractions are phytate and hexakisphosphate (Toor et al. 2006; Darch et al. 2014), while the Fe-bound, Al-bound and Ca-bound phosphates are coming under inorganic P fractions in sewage sludge (Xie et al. 2011a, b). It is needed to convert these unavailable P forms to plant-available forms. It is reported that application of organic wastes along with carbon (Mäder et al. 2002; Criquet et al. 2007) and plants itself releasing molecular signals (Schilling et al. 1998) can enhance microbial population, which ultimately increase the P acquisition. Root occupation with AMF increased the explored soil volume and also increased the uptake of nutrients like P (Ferrol et al. 2019). Recently, Nobile et al. (2019) described that barley and wheat uptake as much P from the sewage sludge applied to soil as they uptake from mineral P fertilizer, while in the case of canola crop more P was recorded in case of sewage sludge applied to soil compared to mineral P fertilizer, which was due to the release of more acids from roots to solubilize unavailable P from sewage sludge.

Poultry manure a growing waste product from poultry industry (FAO 2018) is known for its high P content (Pagliari and Laboski 2012). Use of mineral P fertilizers can be significantly reduced by applying it in its raw form or by composting it into other organic amendments (Redding et al. 2016; Calabi-Floody et al. 2018). Soil P forms and activities of phosphatase have been changed by the application of PM (Waldrip et al. 2011). The combined use of RP and PM proved to be a good strategy to meet plant nutrient requirements (Song et al. 2017). It was testified that chilli and wheat yield has been increased by the application of the mixture of PM and RP (Abbasi et al. 2013, 2015). Poblete-Grant et al. (2019) recently stated that the application of PM + RP mixture to ryegrass significantly increased the growth and P uptake.

7.6 Using Biofertilizers for Enhanced Nitrogen and Phosphorus Availability

Sustaining agricultural production without harming the conservation of natural resources and the quality of the environment are the main considerations of the modern world. The soil is a dynamic matrix that supports plant production. However, in the soil environment plant growth is hampered by various biotic and abiotic stresses, for instance, plant pathogens, weeds, salinity, drought, heavy metals, temperature and flooding conditions (Nadeem et al. 2014; Ali et al. 2017; Mustafa et al. 2019). The excessive utilization of agrochemicals to combat such stresses and recompenses the crop production losses, on the other hand, threatens environmental quality. During the last few decades, significant advances have arisen in understanding soil–microbe interactions for sustainable crop production in an economically sound and ecologically viable option. The plant rhizosphere is home to millions of bacterial species that exhibit growth-promoting effects to plants via direct and indirect mechanisms and recognized as PGPR (Kloepper et al. 1986; Zahir et al. 2004; Kumari et al. 2019). Recently PGPR have gained significant attention of the scientific community for use as biofertilizers for sustainable agricultural production (Khalid et al. 2009). Numerous experiments hitherto have explained the increased crop yield and growth via enhanced nutrient use efficiencies using PGPR-based biofertilizers. Some aspects of PGPR-based biofertilizers in enhancing N and P use efficiencies are discussed.

7.6.1 Plant Growth-Promoting Rhizobacteria and Biological Nitrogen Fixation

Nitrogen is considered as a key mineral nutrient for proper development and growth of the plants and one of the main factors affecting the crop production (Ali et al. 2017). Certain PGPR are equipped with the specialized mechanisms using nitrogenase enzyme to reduce N_2 to NH_4 through a process termed as BNF (Kim and Rees 1994; Jetiyanon 2015). The BNF is a well-studied phenomenon involved approximately two-thirds of the total N fixed globally through diazotrophic microbial communities mostly archaea and bacteria (Dixon and Kahn 2004). Nitrogen-fixing microbes are normally classified as symbiotic (rhizobium-legume/non-legume symbiosis), associative symbiotic (endophytes) and free-living (Azotobacter and Azospirillum spp.) with most of the N fixed through symbiotic N fixing mechanisms (Bashan and Levanony 1990; Zahran 2001; Bhattacharyya and Jha 2012; Kakraliya et al. 2018; Kumar et al. 2018; Layek et al. 2018; Rani et al. 2019). In this regard, symbiotic N fixers develop symbiotic relationships with legume roots and hence leguminous crops took advantage through increased supply of biologically fixed N (Ali et al. 2017; Ahmad et al. 2019; Naseer et al. 2019). However, other agriculturally important crops especially grasses such as wheat, rice, corn, etc., are unable to perform BNF and, hence there is an increasing trend of studies regarding the supply of N through PGPR-based inoculants (Charpentier and Oldroyd 2010; Chamani et al. 2015; Kamran et al. 2017; Picazevicz et al. 2017). Previously, Parmar and Dadarwal (1999) suggested increased nodulation and N fixing ability of chickpea (*Cicer arietinum*) due to inoculation of N fixing *Fluorescent pseudomonads*. In another study, regulation of BNF in soybean production due to applied Brady rhizobium spp. has been well reported (Okito et al. 2004). Very recently, Ahmad et al. (2019) testified increased growth, nodulation and N fixing ability of chickpea with the applied *Paenibacillus* spp. in a jar trial. Summary on a range of studies describing various PGPR mediated plant growth promotion *via* increased atmospheric N_2 fixation is given in Table 7.3. However, for obtaining maximum on-farm benefits from diazotrophic PGPR-based biofertilizers, a systematic strategy that allows for full utilization of all beneficial effects and increases crop yield while minimizing the chemical fertilizer inputs is therefore required (Kennedy et al. 2004).

7.6.2 Plant Growth-Promoting Rhizobacteria and Phosphorus Solubilization

Phosphorus is an essential nutrient as well as one of the main factors affecting the plant growth despite its abundance in the soil as both (inorganic and organic forms). Almost, 95–99% of P in the soil represents the insoluble pool and cannot be utilized by plants (Vassileva et al. 2000). An increasing number of strategies have been documented earlier to convert this insoluble form of P to soluble forms to facilitate plant uptake. In this regard, exploiting the potentials of rhizosphere microbiome has garnered considerable attention worldwide, especially the use of phosphate-solubilizing rhizobacteria in agriculture. These bacteria under their P solubilizing activity convert insoluble P to plant-available forms and are increasingly applied as biofertilizers for better crop production since the 1950s (Kudashev 1956; Kumawat et al. 2009; Anand et al. 2013; Samreen et al. 2019). A range of rhizosphere inhabiting bacteria has shown the ability of insoluble phosphate solubilization falling in the genera *Bacilli*, *Pseudomonas*, *Escherichia*, *Serratia*, *Achromobacter*, *Corynebacterium*, *Erwinia*, *Brevibacterium*, *Xanthomonas* and *Micrococcus* spp. However, among these all, *Bacilli* and *Pseudomonas* are the most dominant inhabitants with varying compositions in plant rhizosphere and non-rhizosphere soil (Kumawat et al. 2017). Certain commonly found PGPR are equipped with specialized mechanisms by which they can solubilize unavailable phosphates to plant-available HPO_4^- (monohydrogen phosphate ion) and $H_2PO_4^-$ (dihydrogen phosphate ion) through lowering rhizospheric pH, dissolving metal phosphate complexes by releasing organic acids and ion exchange processes, and, hence improve crop yields through enhanced nutritional availability to main crop (Kumar et al. 2014; Ali et al. 2017; Saeed et al. 2019; Ahmad et al. 2019). In addition, using PGPR exhibiting P solubilization activity as biofertilizers would not only cut down the high costs associated with mineral fertilizer application in agriculture but also improves the overall quality of the environment (Banerjee et al. 2010). Application of biofertilizers containing beneficial PGPR favours the development of beneficial communities within the rhizosphere associated with increased crop yields (Noor et al. 2020). For instance, in a study, the inoculation of PGPR showing P solubilizing activity increased plant growth and root proliferation of alfalfa plants (Guiñazú et al. 2009). Summary of studies involving the application of biofertilizers based on PGPR is given in Table 7.3.

Table 7.3 Role of different biofertilizers in nitrogen and phosphorus nutrition in crop plants

Nutrient	Biofertilizer type	Crop	Impact	Reference
Nitrogen	*Ustilago maydis* + *Bacillus pumilus*	–	Endosymbiotic N_2-fixing association	Ruiz-Herrera et al. (2015)
	Burkholderia ambifaria Mex-5	Grain amaranth (*Amaranthus*)	Promote grain yield	Parra-Cota et al. (2014)
	S. paucimobilis ZJSH1	Dendrobium (*D. officinale*)	Improve N fixation	Yang et al. (2014)
	Paenibacillus polymyxa P2b-2R	Red cedar (*Juniperus virginiana*)	Promote N fixation	Anand and Chanway (2013)
	Paenibacillus polymyxa P2b-2R	Lodgepole pine (*Pinus contorta*)	Enhances the growth of pine seedlings	Anand et al. (2013)
	RILs 34/104+ *Rhizobium tropici* CIAT899	Common bean (*Phaseolus vulgaris*)	Improve N fixation	Tajini and Drevon (2014)
	Bacterium BJ-18T	Wheat (*Triticum aestivum*)	Can improve N fixation	Wang et al. (2013a, b)
	BNF	Green foxtail (*Setaria viridis*)	Enhance growth	Pankievicz et al. (2015)
	Paenibacillus polymyxa ANM59	Chickpea (*Cicer arietinum*)	Improve growth of crop and soil fertility	Ahmad et al. (2019)
	R. huautlense	Dwarf willow (*Salix herbacea*)	Form nodules in flooded and non-flooded soils	Wang and Martinez-Romero (2000)
Phosphorus	*Paenibacillus* sp. ANM76	Chickpea (*Cicer arietinum*)	Improve P solubilization	Ahmad et al. (2019)
	Phosphate-solubilizing bacteria + organic acids	Rice (*Orzya sativa*)	Enhance P solubilization	Panhwar et al. (2013)
	Phytate mineralizing bacteria (PMB)	Common bean (*Phaseolus vulgaris*)	Increase P availability	Maougal et al. (2014)
	Phosphate-solubilizing bacterial (Ps-5, Ss-2)	Sunflower (*Helianthus annuus*)	Strong positive relation b/w phosphate solubilization and organic acid production	Shahid et al. (2015)
	Bacillus circulans (CB7)	Tomato (*Lycopersicon esculentum*)	Positive response for seed germination, plant	Mehta et al. (2015)

(continued)

Table 7.3 (continued)

Nutrient	Biofertilizer type	Crop	Impact	Reference
			growth and P solubilization	
	A. chroococum + *A. brasilense* + 30 kg ha^{-1}	Rice (*Orzya sativa*)	Improve growth and yield	Yadav et al. (2014)
	Pseudomonas fluorescens (DR54)	Maize (*Zea mays*)	Enhance P soluble soil pools at the early growth stage	Krey et al. (2013)
	Arsenic-resistance bacteria (*P. vittata*)	Tomato (*Solanum lycopersicum*)	Improve plant growth and nutrition	Ghosh et al. (2015)
	Burkholderia sp. (MTCC 8369) and *Gluconacetobacter* sp. (MTCC 8368)	Rice (*Orzya sativa*)	Improve P uptake, growth and yield	Stephen et al. (2015)
	RILs 34/104+ *Rhizobium tropici* CIAT899	Common bean (*Phaseolus vulgaris*)	Improve P utilization efficiency	Tajini and Drevon (2014)
Potassium	Potassium solubilizing bacteria (XF11) + k-feldspar powder	Tobacco (*Nicotiana tabacum*)	Increase in K and N uptake by tobacco seedlings	Zhang and Kong (2014)
	P-solubilizing (*Bacillus circulans* CB7)	Tomato (*Solanum lycopersicum*)	Improve plant growth and K solubilization	Mehta et al. (2015)

7.7 Conclusions

Nitrogen (N) and phosphorus (P) are the most important plant macronutrient, and their management is necessary for sustainable agriculture. Managing N and P in agroecosystem via smart use, limiting their losses and increasing use efficiency are major pillars and very much needed in modern-day agriculture practices. Nitrogen reserve in the atmosphere, though enormous, but require extensive utilization of fossil fuel for its conversion to plant usable form. Biological nitrogen fixation can be an alternative good option to opt. For P conservation, smart use of rock phosphate must be adopted to increase the life of remaining reserves. Involvement of precision agriculture, smart fertilizer modulation and minimizing fertilizer loss can be a major contributor to efficient N and P use in agriculture.

7.8 Future Perspectives

Although, plenty of work has been done for increasing the efficiency and reducing loses of nitrogen (N) and phosphorus (P) fertilizers in modern agricultural systems and practices but still there is huge gap to improve. New methods of availing N and P to plants can be found in which fewer natural resources are used. Integrated approaches may be used to enhance nitrogen and phosphorus use efficiency, i.e. good agricultural practices, 4R fertilizer placement, site specific application of fertilizers, use of innovative fertilizers, organic fertilization and improving the soil health and fertility status. Use of soil and atmospheric biota for providing N and P to plants can be a good option but proper understanding of mechanism and adoption for meeting the crop requirement is still needed. Soil fixed P can be converted to plant usable forms by the means of chemical as well as biological approaches. As P stocks of natural resources are very limited in the world and vanishing rapidly so there is a need to enhance the fertilizer use efficiency and reducing its loses in agro-ecosystem. P solubilizing microbes can be proved helpful for converting soil fixed P into labile pools but extensive screening and selection of microbes is required for this purpose. Climate smart fertilizers and slow-release fertilizers are good approaches to enhance the fertilizer use efficiency and reducing the fertilizer loses up to a certain range but a room is present in this field to further enhance the efficacy of these products.

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